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AGE CANNOT WITHER OR VARIETIES OF GEOLOGICAL EXPERIENCE.[1]

IRA B. JORALEMON.

ABSTRACT.

Economic Geology may be practiced in two widely differing ways. Each has its uses and its limitations. First is the meticulous, detailed study of ore occurrences and of the process of ore deposition. This careful work has resulted in nearly all of the progress in the theory of ore deposition, and in the discovery of much of the ore in great districts. Its chief limitation comes from the shortness of human life and the time required for detailed study. Conclusions must either be based on a limited number of observations by one geologist or on observations by several who may have different methods and points of view.

The second method, which is the principal subject of the paper, involves rapid and often inadequate visits to many hundred occurrences, with the economic factor always in view. There must be a ground work of thorough study to permit accurate appraisal of essential features. While this method often seems casual, it has resulted in the development of many mines. And the study, even though brief, of many hundred occurrences by one observer may be useful in helping to appraise the theories advanced by those who specialize in detailed research.

Examples are given of the variety in occurrence and in probable genesis of many orebodies that seem at first to belong to the same types. Generalizations have usually proved to be either wrong or of limited application.

Both methods of practicing Economic Geology are useful. The second, which may be called Comparative Economic Geology, has the added attraction of physical and intellectual adventure.

A Presidential Address before this challenging audience would normally demand erudition. And so for a long time I have been planning a paper on the value and use of statistics in geology and mine examination. A friend suggested the happy title of "The Fallacy of the Average." The subject is an exceedingly important one, and it should be interesting. But like many statistical studies, it is far from simple. The ideas became more and more involved

[1] Presidental Address given at the Annual Meeting of the Society of Economic Geologists, Detroit, November 9, 1951.

until I despaired of understanding them myself, to say nothing of making them clear in an evening's talk.

As I worked on this mathematical analysis it dawned on me that it was not because of any deep study of an abtruse problem that you have honored me with this office. If I have made any contribution to our profession, it has been the result of a bird's eye view of many problems rather than thorough research on a few. And so it seems more suitable to tell something about the sort of Economic Geology I have practiced—the reason for it and its relation to the profession as a whole. This is really a sort of "apologia pro vita mea." A few examples out of nearly a thousand mines and prospects that I have visited may give some idea of the impact of many different occurrences on geological theory. At the same time I hope I can pass on to you a little of the interest and the spirit of intellectual, as well as physical, adventure that have come from association with so many friendly and thoughtful people, and so many equally friendly and thought-inspiring rocks. It is such a fascinating world that we can say of her far more truly than of Cleopatra that

> "Age cannot wither her, nor custom stale
> Her infinite variety."

DETAILED GEOLOGIC RESEARCH.

Economic Geology may be practiced in two widely differing ways. Each, I think, has its uses and each has its limitations. The first is the meticulous, detailed study of individual districts and orebodies, and of the process of ore deposition. This work calls for the highest type of patient, intelligent research. The remarkable investigation of rock alteration and of vein deposition in Butte, by Reno H. Sales and Charles Meyer, is an outstanding example of this approach to geological problems. The work of the United States Geological Survey and of many State Surveys and universities has made equally valuable contributions to our geologic knowledge. Nearly all progress in the understanding of ore occurrence has resulted, and will continue to result, from thorough mapping and study of details, supplemented by laboratory work where possible. Even when the practical application of the research is not evident, it is worth while for the reason that no one can foretell what line of investigation may lead to the most important results. President Conant summarized the value of such endeavor beautifully in the title of his talk of a few years ago, "The Revolutionary Nature of Useless Knowledge."

The accomplishments of this method of geologic study have been so unquestioned that there is a temptation to overlook its limitations. Of course, all human efforts have their defects. The most serious one in detailed geologic research comes, I think, from the shortness of human life. Detailed study takes a long time, and such work by any one man must be limited to a comparatively small number of areas or problems. This means that generalizations on the theory of ore occurrence by those whose scholarly method qualifies them to make such deductions, must depend either on a small number of cases, or on the observations of many geologists rather than of one. This is more serious in the case of geology than in sciences in which important experiments

can be checked in the laboratory by several investigators. Even where geologists are of the highest caliber, they often see differently. This is illustrated by the testimony in mining lawsuits. In a famous case, one eminent geologist of unimpeachable honesty, swore that there was a vein in a short crosscut, and another of equal ability and character swore there was no vein. As in many instances, the testimony regarding geologic phenomena depended on interpretation, subconscious or otherwise, rather than on demonstrable fact. There are many other instances in which papers or reports by different geologists are not strictly comparable. Deductions from these reports are subject to question.

Generalizations that are based partly or wholly on published statements may be faulty because the accuracy of underlying field work is often unknown. Careless or lazy observers often write in a most convincing manner. Even where field work has been excellent the evidence may be incomplete because company policy has prevented the publication of results of important examinations, or has permitted the release of only partial data. Altogether, geologic literature is an inadequate foundation for theories regarding ore occurrence.

Another limitation of the scholarly geologic method comes from the almost irresistible temptation to emphasize articles by others that support a theory, rather than those that oppose it. This emphasis is often entirely unconscious. But it, together with the inadequate number of occurrences on which detailed data are available, tends to make the evidence on which a conclusion is based statistically faulty.

A final source of possible error is to accept too completely a conclusion advanced by one of the great members of the profession. It is hard to keep in mind the fact that the work, even of a great geologist like Lindgren, included study of a limited number of geologic exposures that may not have been truly representative. The theories advanced by the greatest scientists may satisfy known observations, but may prove to be true only under limited conditions.

Sometimes examples from another science help us to appraise the limitations of our own. I have been much impressed by two examples from medical history that were given to me by a friend who has specialized in research on tropical diseases. One of them illustrates statistical error, and the other a mistaken acceptance of a conclusion by one of the greatest of all medical research scholars. The first concerned an inoculation against bubonic plague that was developed a few years ago in Madagascar. The American army doctor, who was sent to study the results, reported that the French doctors were confident that evidence of several tens of thousands of inoculations proved that immunity was about 80 percent effective. The data were turned over to a statistician for comment. He found that those who had been inoculated had come to the medical offices voluntarily, following appeals in newspapers and in speeches by officials. They were, therefore, somewhat superior in intelligence and in economic status to the average of the natives. As a result, they probably were afflicted with fewer of the fleas that carry the infection. The statistics that at first glance seemed conclusive really meant nothing.

The second medical instance was the study of a yellow fever epidemic in

Guayaquil in 1918 by the great Noguchi, of the Rockefeller Foundation. Noguchi found an organism called leptospira in the blood of many yellow fever patients. He proved that injection of leptospira into the blood of monkeys gave them all the symptoms of the disease. For years no one questioned Noguchi's conclusion that leptospira were responsible for yellow fever, in spite of the failure to make an effective vaccine or serum from this organism. It was only in 1927 that the Yellow Fever Commission of the Rockefeller Foundation, working in Africa, identified many cases of yellow fever, but found no leptospira. Further research discovered the virus that was really the culprit. This discovery resulted in the vaccine that has done away with the menace of yellow fever. It was later proved that the disease associated with leptospira was an unusual variety of jaundice, clinically indistinguishable from yellow fever but caused by a different organism. The development of the immunization had been delayed ten years by the unwillingness to question the findings of one of the greatest figures in preventive medicine.

Geologists have sometimes been open to similar charges, though fortunately the errors do not result in the loss of thousands of lives. Theories of ore deposition, advanced by the greatest in our profession, have often been accepted as of general application for many years before additional evidence proved that they can not be applied blindly. The classification of orebodies and of minerals, according to temperature of formation, is a case in point. Valuable as this classification is, it has its exceptions. For instance, scheelite is classified as a mineral deposited under mesothermal or hypothermal conditions. This grouping was accepted so whole-heartedly that when scheelite crystals were found on the lower sides of boulders in the glacial detritus at Stibnite, Idaho, evidently deposited there from cold water, the first reaction of some of the best economic geologists was, "It can't be so. It must be placer scheelite." There was placer scheelite, to be sure, but the crystals on boulders could no more have been of direct placer origin than the leaf-like gold crystals that are often found plating the downstream side of boulders above bed rock in gold placer deposits.

Other instances have helped to prove that the classification of minerals according to temperature of formation is a useful hypothesis, and not an inviolable law. For instance, laboratory work is proving that metallic sulphides and other minerals can, under the right conditions, be formed at far lower temperatures than was formerly thought possible. We do not yet know the whole truth.

Many of the famous controversies that have enlivened Economic Geology have resulted from enthusiastic and brilliant generalizations that took in too much territory. Mr. J. E. Spurr's Vein Dike theory is a notable example. No one who has looked at a great number of vein deposits can have failed to meet with cases where heavy vein magmas seem a reasonable explanation. In other instances the vein-dike theory seems remote from the facts. A generalization on either side of the fence is unsatisfactory.

A long standing argument about the origin of the remarkable gold reefs on the Rand is another example of a controversy in which, perhaps, neither side is wholly right. The concentration of values in extremely thin beds,

sometimes less than an inch thick, over hundreds of square miles is too fantastic a phenomenon to admit of any simple explanation. Rather than trying to force the occurrence into syngenetic or hydrothermal deposition, might it not be more constructive to say that we just don't know. The evidence is not yet conclusive. Perhaps some day an unprejudiced analysis of more complete data may point to a solution no one has yet thought of.

The fact is that we have not sufficient reliable evidence to form a dependable statistical basis for hard-and-fast generalizations or laws of ore occurrence.

Josh Billings made a profound contribution to philosophy when he said, "'Taint the not knowing that adds so much to the sum of human ignorance as the knowing so much that ain't so."

COMPARATIVE ECONOMIC GEOLOGY.

In spite of its limitations, no one questions the great value of the geologic method that depends on thorough detailed study. But the limitations suggest that there may be a useful place in the profession for the second method of geologic investigation.

Those of us who belong to this second group of economic geologists try to arrive at a pattern of ore deposition from visits to many hundred mines, rather than from detailed study of a few. This involves an attempt to relate and compare many areas and types of orebodies, noting the points of resemblance without losing sight of essential differences.

This variety of geologic study, which may be called Comparative Economic Geology, was a natural outgrowth of the scout or "field man" of 50 years ago. The field man knew that at best one in thirty or forty of the prospects he examined might turn out to be at least a small mine. Therefore, his only hope of success lay in visiting hundreds of properties, before someone else grabbed the good ones. The successful field man had to grasp the essential details of ore occurrence quickly. He had to be right in most of the deductions, or his job was gone. Slipshod as his methods seem to the research geologist of today, the "field men" found many of the great mines that have given this country predominance in metal production.

The present day comparative or examining geologist tries to use more scientific methods, but still works rapidly. As nearly all new orebodies do not outcrop, but are found by geologic deduction, he must have a thorough grounding in geologic mapping and theory. But he seldom has time to carry out any detailed study. His greatest asset is a wide range of experience that enables him to see, almost at a glance, the facts that are essential. He must decide in a few hours whether or not further work is justified. Sometimes a detailed geologic study, and sometimes underground development or drilling, will be most effective in proving or disproving the presence of a workable orebody. The economic side is always to the fore—the relation between the possible value of the orebody, the degree of doubt, and the cost of proving the theory. In simpler terms, is the pot worth the ante?

We examining geologists must depend almost completely on our own observations and conclusions. Almost every new mine has been condemned by

several engineers or geologists—often men with great and deserved reputation. Therefore, if we accept the recommendations of others we will seldom think it worth while to make an examination—and will almost never find a new mine. In order to stand any chance of success, we must see every problem from a new and personal point of view, entirely apart from the ideas of others. When we can, we read reports or articles on a new area, and so save time through knowing in advance the underlying geologic setting. This helps us to form some idea as to what to look for. But we pay little attention to the conclusions of others unless the problem is so simple that the answer is self-evident. Often there are so many properties waiting to be examined that a search for earlier data is impracticable. The work of those of us who visit many hundred mines is almost always sadly incomplete, but it is our own.

This method of evaluating mines or prospects is in great contrast with the detailed, comprehensive study that finds much of the new ore in great districts like Butte. It is just as foreign to the technique of those who specialize in theoretical geology. It seems an unscientific, rule-of-thumb method of attack, to both of these more scholarly groups. The reasoning often resembles a hunch rather than a carefully thought-out theory. Luck seems to play an unduly large part in the outcome. But luck is often another name for subconscious deduction based on wide experience. Pasteur expressed it much better in the phrase, "Chance favors the prepared mind."

In addition to the direct practical application to the search for new mines, this comparative geology, based on hundreds of examinations, can be useful in helping to appraise the truth and the universality of geologic theories. The comparative geologist seldom spends time enough on one problem to originate an important theoretical idea. But if he is mentally alive, he must keep in mind the generalizations that have been advanced by geologists who follow the method of thorough research. The theories help him to appraise new occurrences, and the observation of many occurrences throws light on the validity of the theories. He must concentrate on variety, and unless he is blind the variety will keep him from becoming wedded to any one concept. As Descartes said, we must doubt everything, and have faith only in our own doubt. Progress can be made only when there is readiness to abandon theories the moment new evidence proves that they are inadequate. And often, illuminating evidence comes from the comparison of many widely varying occurrences by one who has seen them himself.

Of course Comparative Geology also has its limitations. The hasty examinations often make us overlook important facts of occurrence. We tend to jump at conclusions. Resemblances that seem to indicate definite types of orebodies often prove to be accessory and not fundamental. No matter how much deposits seem to have in common, their unexpected differences often make fools of our generalizations. Nature is too varied to be compressed into any definite molds.

EXAMPLES, VALUE, AND DANGER OF COMPARATIVE GEOLOGY.

A few examples out of the thousand or so examinations I have made will do more, I hope, to show the value and the danger of Comparative Geology

than further talk on principles. With the exception of a couple of interesting occurrences that were described in conversation with friends, all the observations that follow are from my own experience. The failure to quote others is deliberate, in the hope that it may emphasize the method. Often the descriptions and conclusions conflict with published articles by others that are surely, in some cases, more nearly correct. Confining the examples to my own field work may open up the way to brickbats of criticism, but it will help to appraise the sort of geology I have practiced.

Red Beds Copper Deposits.

One of my best lessons in the versatility of Nature came from a study of the Red Beds copper deposits that started nearly 40 years ago. The excellent descriptions of many of these deposits in, "Ore Deposits of New Mexico," (Prof. Paper No. 68 by Lindgren and Graton) suggested that there were so many small and moderate sized orebodies in the Permian sandstone that somewhere there should be a great one. Dozens of visits over several decades failed to find the great orebody. However, they proved to my satisfaction at least, that instead of one type there were many different characters and origins of the Red Beds copper deposits.

The first examinations were in the wide band of Permian sandstone and shale that outcrops through central Texas. Copper showings in the sandstone were reported over a large area, and optimists thought the mineralization was in a widespread continuous bed. Examinations of many deposits in Jones and Knox counties showed the orebodies had in common the occurrence in green shale, sometimes extending into the red sandstone above and below the shale. Chalcocite, with some pyrite, replaced fragments of charred wood or other organic remains, or formed films on the shale bedding. Much of the chalcocite had been oxidized to malachite and azurite, with kernels of glance in harder fragments. The copper content varied from 2 to 5 percent.

Thus far the deposits had lived up to the claims of promoters. But a hurried mapping showed that instead of one horizon, the ore in different localities occurred all the way from near the top to near the bottom of the thick Permian formation. And individual deposits were in small cross-bedded basins, never more than 1,000 feet long, 50 feet wide, and a few feet thick. The copper-bearing beds feathered out at the margins. The conclusion was inescapable that the copper had been deposited, at wide intervals of time, in the muddy bottoms of slow moving streams. It had probably been brought in by the surface water from some unknown source far to the west.

The Zuni Mountain deposits, in the western edge of New Mexico, proved to be of a completely different type. The core of the mountains is made up of granite, gneiss and schist, probably Precambrian. Around the flanks are mesas of arkose, shale, and sandstone of Permian and later ages. The older metamorphic rocks are mineralized along sheer zones with pyrite and a little chalcopyrite, oxidized to lean malachite ore near the surface. This mineralization resembles the roots of a disseminated copper deposit. In the lower 60 feet or more of the Red Beds adjacent to the older rocks, usually only a few feet below the present surface, malachite, azurite, and chalcocite occur in seams

in shale, replace petrified wood, or replace the cementing material in conglomerate or sandstone. The copper-bearing beds contain from a few thousand to hundreds of thousands of tons of 1 to 3 percent copper ore.

These Zuni Mountain Red Beds deposits called to mind the thin bed of recent copper-bearing sandstone and conglomerate, that outcropped in a canyon that cut across the disseminated copper deposit at Ray, Arizona. Similar recent copper-bearing conglomerate lies on the flanks of the submarginal copper and iron sulphide mineralization in Red Mountain, near Patagonia, Arizona. Like them, the Zuni Mountains deposits probably received their copper through the agency of surface water, from eroded parts of the adjacent low grade pyritic deposits in the older rocks.

A third type of Red Beds copper deposits is the Big Indian, east of Moab, Utah. Here a 10 to 15 foot bed of sandstone and conglomerate, 800 by 300 feet in area, was mineralized with chalcocite, malachite, and azurite, replacing organic remains and the cement between sand grains. The 1 to 3 percent ore was flat lying, just under the thin cap rock of a mesa. A second bed, 30 feet deeper, was similarly mineralized, but averaged less than 1 percent copper. The southwest limit of both copper-bearing beds was a fault that dipped 45 degrees northeast. In other directions the values gradually faded away. The actual intersection of the fault with the upper copper-bearing bed had been eroded away. At the intersection with the lower bed there was a lens of rich chalcocite-covellite-pyrite ore, with the sulphides cementing sand grains. A caved 185 foot incline on the fault was said to have developed lean copper mineralization to the bottom. It seemed likely that copper-bearing solutions had risen along the 45 degree fault and spread out in the two flat favorable beds, depositing copper sulphides in both structures.

A fourth type of Red Beds copper deposits was illustrated by the orebody at Pastura, New Mexico, that was mined some years ago by I. J. Stauber. A 3 to 12 foot flat bed of sandstone and conglomerate, overlain by green shale, was mineralized with malachite, azurite, and chalcocite, often replacing fossil wood. The grade of ore averaged nearly 5 percent in an area 1,500 feet long by 220 to 350 feet wide. The maximum thickness of barren capping was less than 30 feet. The highly silicious ore was shipped to the El Paso smelter as flux. The excellent profit was due partly to the low smelting and freight rates, but still more to the fact that the entire mechanical equipment consisted of one mule.

The most remarkable feature of the Pastura deposit was a bed of pure white clay that lay immediately under the ore. The clay was from a few inches to 10 feet or more in thickness. The top of the clay was undulating, sometimes rising 6 feet in the same horizontal distance. As the top of the ore had a uniform, very gentle slope, the thickness of ore varied inversely with that of the clay. Though the sandstone bed in which the ore occurred continued over a great area, the copper mineralization was confined almost entirely to the portion of the area that was underlain by the clay.

The origin both of the white clay and of the ore at Pastura is a mystery. Microscopic study of the clay indicated that it was a quartz-sericite schist derived from weakly metamorphosed sandstone. This diagnosis seemed ex-

ceedingly dubious. Under a hand lens the clay looked like the completely kaolinized quartz porphyry dikes that often accompanied oxidized copper ore in Bisbee, Morenci, and other southwestern copper districts. The close physical association of clay and ore suggests some causal relation, but no one knows what this relation may be. This most valuable of the Red Beds copper deposits is also the most puzzling.

The many other Red Beds copper deposits that were visited differed in detail from these four, but bore some resemblance to at least one of them. The remarkable differences between these orebodies suggest that there may be no one type of Red Beds copper deposits, but that orebodies of many different origins have chosen as their locus various sandstone beds, with carbonaceous matter as an important precipitant.

Akin to the Red Beds copper deposits, in some degree, is the great White Pine orebody of Copper Range Company, in the northwest corner of the upper peninsula of Michigan. In the White Pine, gently rolling beds of shale and sandstone in the Nonesuch Shale Formation are mineralized with chalcocite, and a little native copper, pyrite, and silver over an area of many square miles. Two or three hundred million tons may eventually be mined. In an 8 foot bed of "Parting Shale" the mineralization is remarkably uniform, averaging about 1.25 percent copper. In other standstone and shale beds, above and below the Parting Shale, only part of the area assays more than 0.8 percent copper. The ore has been developed on both sides of the steep White Pine Fault, that has a vertical displacement of about 1,300 feet and that is itself mineralized. Sandstone beds 50 to 100 feet below the Parting Shale are impregnated with chalcocite and native copper, with unusually high silver values, for 1,000 to 2,000 feet away from the fault.

The origin of the copper in the White Pine is as uncertain as that of copper in the Permian Red Beds. Some suggest that it may have been deposited in a muddy basin, with copper brought in by meteoric water from eroded portions of the older copper-bearing amygdaloidal lavas of the Lake Superior area, and precipitated as chalcocite by the syngenetic pyrite in the mud. If this is the true origin, there must have been much solution and redeposition to carry the copper into the less continuous orebodies in the nearby sandstone beds, or along the White Pine Fault itself. An alternative theory is that the copper was introduced by hydrothermal solutions that arose along the White Pine and other faults, and spread out along the favorable beds for several miles from the fault, with copper precipitated by syngenetic pyrite, organic matter, by iron in the shale and sandstone, or simply due to change in pressure and temperature. This theory fails to account for the fact that the Parting Shale mineralization does not vary with distance from the Fault, or for the much more widespread and uniform ore in the impervious shale, than in the porous sandstone and conglomerate above and below it.

As in the case of the Red Beds deposits, we do not know the answer, and there may not be any one answer to the question as to the origin of the White Pine copper.

The extensive copper deposits in red sandstone at Corocoro, in Bolivia, differ from the Red Beds deposits of the Southwest in that the beds dip

steeply, and most of the copper is in native form. However, a rich chalcocite orebody occurred along a steep fault that was almost parallel with the bedding. Similar but smaller copper deposits in red sandstone occur at intervals for more than 100 miles south of Corocoro. A hydrothermal origin seems likely for the Corocoro deposits. They emphasize again the occurrence of bedded copper orebodies in red sandstone in many parts of the world, and the fact that no one type of genesis seems likely for all the deposits.

Uranium Deposits in Sandstone.

Recent visits to several of the bedded uranium ore deposits in southwestern states have added to the interest and variety of the study of orebodies in sandstone. The Happy Jack mine in southeastern Utah may be cosidered an intermediate form between Red Beds copper deposits and the carnotite orebodies of the Colorado Plateau. In stratigraphic position, the Lower Triassic Moenkopi Formation in which the ore occurs, is between the Permian Red Beds that contain most of the ordinary sandstone copper orebodies, and the Jurassic Salt Wash member of the Morrison Formation that contains most of the carnotite bodies. The Happy Jack bed is from 2 to 12 feet thick and the area is large enough to make it an important orebody. The ore consists largely of pyrite, chalcopyrite, and bornite replacing and cementing sand grains. With these sulphides are notable amounts of pitchblende. Near the surface the ore is partly oxidized to chalcocite, malachite, azurite, and secondary uranium minerals, principally torbernite. In form the orebody is in many respects like the Plateau carnotite deposits. A cross-bedded channel in the sandstone is probably the best defined control. Intersecting fractures, and possibly a gentle fold, also seem to have played a part in localizing the ore. Until further development is completed, it is largely a matter of opinion whether old channels or fractures are more important guides. If not for the resemblance to the Plateau carnotite deposits, most geologists would feel confident that the Happy Jack orebody is of hydrothermal origin.

Another district of a transitional type includes the uranium-vanadium orebodies in the Lukachukai Mountains of northeastern Arizona. These are bedded deposits in the Salt Wash sandstone. The flat lying beds are near a sharp fold in the sediments, with probable faulting along the axis. The ore is near the tops of several mesas that are separated by valleys in which the orebearing bed has been eroded away. There is a marked change in character of ore between deposits in the southeastern mesas and those in the northwestern mesas. In those farthest southeast the carnotite and other secondary uranium and vanadium minerals, with a little pitchblende, are associated with abundant limonite, calcite, and gypsum. There are remnants of pyrite, and a little galena. In several places there is a marked change in character of material at vertical fractures or shear planes. For instance, one tunnel has exposed 10 feet of soft limonitic ore on one side of a vertical fracture, and hard sandstone partly replaced by calcite on the other. In the mesas further northwest the limonite, calcite, and gypsum become progressively less abundant, until in the most northerly developed orebodies the ore consists of uranium

and vanadium minerals cementing sand grains, with few other gangue minerals. The hurried examination suggested that the primary ore was zoned outward from a source of hydrothermal mineralization in the southeastern part of the district.

The final step in the succession of uranium orebodies in sandstone is to the normal Colorado Plateau carnotite deposits in sandstone beds of the Salt Wash member of the Morrison or in the Entrada sandstone. It has been thought, with much reason, that cross-bedded channels of old streams have localized the ore, and that trunks of trees and other vegetable matter have been largely responsible for precipitation of the carnotite and the accompanying vanadium minerals. The uranium and vanadium minerals have usually been considered as syngenetic or diagenetic.

A casual study of one deposit, and comparison with the Lukachukai and Happy Jack deposits, throw some doubt on this theory. In several places the size and grade of ore changed notably at vertical joint or shear planes. This observation was checked by the intelligent miner—and the comments of those who have to make money out of an orebody are always worth considering. In places ore occurs in three beds one above another, all making away from the same steep shear plane, and separated by 5 to 15 feet of barren sandstone and shale. The general form of the stopes is much like that in lead-zinc deposits in limestone in the Central states.

If the uranium-vanadium mineralization was brought in by surface streams, either at the time of deposition of the sandstone or a little later, the conditions necessary for its formation must have recurred many times. In the Colorado Plateau itself and the districts southwest of it, orebodies of more or less similar character have been found in ten or fifteen different beds, scattered through more than 1,500 feet of sediments that represent eighty or a hundred million years of geologic history.

The uranium deposits in sandstone are nearly as varied as the sandstone copper deposits. Considering the great variety of the occurrences, any one explanation is subject to question. And acceptance of any one theory of ore formation may lead to missing a lot of ore.

Breccia Chimneys.

Orobodies in breccia chimneys are as diverse and puzzling as those in the Red Beds. Comments on them could easily fill a long book.

A study, extending over 40 years, of the dozens of chimneys in the Old Hat District on Copper Creek, north of Mammoth, Arizona, has proved extremely interesting, though quite the opposite of illuminating. Incidentally, it proved to be an expensive luxury to the mine owners. Early development in the Old Hat District found many hundred thousand tons of enriched 2 to 4 percent chalcocite ore in seven or eight of the chimneys, under 100 to 300 feet of limonitic oxidized material. Individual pipes were from 50 feet to nearly 400 feet long, and up to 300 feet wide. Fragments in the chimneys were usually of the adjacent wall rock, in some places andesite and in others intrusive diorite. The chalcocite and pyrite accompanied soft sericitic material between

the fragments. With dozens of chimneys that looked on the surface just as good as the ones that were first developed, the Old Hat seemed a very promising district.

Then Nature stepped in with her unexpected variety. A tunnel only 150 feet vertically below the crest of the large "Superior" breccia outcrop found only pyritic, partly sericitized diorite with no breccia and no copper, and no fractures or veins of any notable size. Drillholes under the beautiful Wisconsin and Minnesota outcrops found breccia cemented by pyrite and sericite, with almost no copper. Other chimneys proved equally disappointing.

While deeper levels under the original enriched orebodies usually found low-grade primary breccia mineralized with pyrite and chalcopyrite, the Prince chimney afforded another surprise. At 200 feet depth a flat lying lens cutting across the lean breccia contained several thousand tons of almost pure chalcopyrite. Two hundred feet deeper, all that was left of the chimney was an open fissure partly filled with large pyrite and quartz crystals, cutting solid diorite.

At least two good looking copper stained breccia outcrops in the Old Hat District turned out to be thin sheets of breccia underlain by slightly pyritic diorite or andesite. Still another chimney proved to contain a large body of 1 percent molybdenum ore, which yielded the only profit that has been made in the District. No copper orebody has been found except for the seven or eight that were developed more than 40 years ago. There seemed to be no limit to the variety of mineralization in the Copper Creek chimneys, and no limit to the amount that could be spent in a fruitless hunt for more ore.

The large chimney at the Panuco Mine in Coahuila, Mexico, was remarkable in that the outcrop, now removed by open pit mining, was apparently just above the top of the breccia. The part of the outcrop that remained at the time of examination consisted of slightly altered iron stained syenite. At a few feet greater depth the pit showed large and small fragments of syenite, separated by masses of pegmatitic quartz, coarse mica, feldspar, and limonite, with a little copper stain. Then came typical leached breccia, with syenite fragments cemented by limonitic material. At 100 feet depth chalcocite ore assaying about 5 percent copper was encountered. This enriched zone was about 100 feet deep. Below it the copper content gradually decreased to little more than 1 percent on the deepest level, 600 feet below the surface. The breccia continued with little change in dimensions.

The evidence suggests that if the erosion surface had been 50 feet higher there would have been no sign of the Panuco chimney, save perhaps for a little iron staining on fractures in the syenite.

Other breccia chimneys in many parts of the world have been equally challenging and unpredictable. One large pipe in the Royal Development Company property in the Cascades has slightly altered angular fragments of granitic rock suspended in fine-grained chlorite, with a small amount of pyrite. Along one margin on the bottom or 1,600-foot level the chlorite gives place to a lens of almost pure chalcopyrite. Unfortunately, there is not much of this high grade ore. A few miles to the north is the Glacier Peak Mine, where the outcrop looks like a typical copper-bearing breccia chimney.

Underground, instead of moderately small angular fragments there were great masses of slightly mineralized diorite, separated by chalcopyrite and molybdenite-bearing cementing material. This suggests a transition stage between a true breccia chimney and a fracture zone deposit. Over the ridge east of the Glacier Peak is the Chelan Mine of Howe Sound, with a great mineralized shear zone—almost a vein. For some unknown reason the copper deposition in these three mines, in the same mineralized area, is of three entirely distinct physical types.

A family of half a dozen or more breccia chimneys between the Moctezuma and the Sonora Rivers in Sonora, Mexico, were surprising in that while the copper minerals were fairly uniformly distributed, one side of the "Washington" chimney contained hundreds of thousands of tons of ore that assayed 0.5 to 1 percent tungstic oxide, in the form of beautiful green stained scheelite crystals. The rest of the chimney contained almost no scheelite. In another chimney the limonitic cementing material in the outcrop gave place a little below the surface to abundant tourmaline, with little sulphide. Other chimneys contained low grade copper ore, or pyritic breccia.

In the Cupric Mine in Utah one side of a large chimney contained 0.2 to 0.3 percent WO_3 in scheelite, but there was no other mineral of possible commercial value.

Breccia chimneys vary as greatly in the relation of fragments to wall rocks as they do in mineralization of the cementing material. In most of the hundred or more chimneys I have seen, the fragments are either of the adjoining wall rock or of a rock that forms a wall of the chimney at a slightly different elevation—usually higher. Sometimes, however, the fragments have been transported many hundred feet, either up or down.

Reno Sales has told me of two breccia pipes in Cananea that are completely different in character and in mineralization, though they are only 1,500 feet apart. The Oversight pipe is elliptical, with a long dimension of 250 feet. From surface nearly to the 800 level the wall rock is limestone, and on the 800 level itself one wall is quartzite and one granite. The pipe filling down to below the 800 level, which is the deepest level, consists largely of loose lying fragments of limestone with a few quartzite fragments. Though some of the fragments are pyritic, no post-breccia mineralization with copper, or even with quartz or pyrite, was found.

The Capote pipe, 250 feet in diameter, cuts limestone to the 600 level, quartzite from 600 to the 1100, and granite from the 1100 to the 1600, the deepest level. On the 1600 level the greater part of the area of the pipe consisted of densely compacted coarse granite fragments cemented by chalcopyrite and pyrite. A smaller portion was filled with rounded quartzite pebbles 3 to 6 inches in diameter, resembling stream pebbles, firmly cemented by chalcopyrite, bornite, and chalcocite.

Mr. Sales suggests that both of these pipes were bored upward by gases that rose from deep sources under high pressure. Mineralizing solutions followed in the Capote pipe, but there was no such follow-up mineralization in the Oversight.

The relation between the true breccia chimneys and the great masses of

breccia like those in the Sudbury District in Ontario is another problem. The physical resemblance of the two varieties of breccia, in spite of the entirely different shape of the bodies, must be taken into account in any general study of breccia. The very great masses of mineralized breccia, often in chimney or modified chimney form, in Bisbee, Nacozari, Braden, and many other places add to the variety of the general study of breccia deposits.

It is inconceivable that all breccia chimneys were formed by the same process. Some of them, like those Mr. Sales describes at Cananea, seem to be most easily accounted for by explosive volcanic activity followed by subsidence in the vent, with later mineralizing solutions coming up along a fissure under the vent. This is particularly likely because most of the chimneys are in volcanic areas. Other chimneys, with exactly similar breccia, show no evidence of explosions, or of transportation, or rounding of fragments. They may have been formed by partial replacement by mineralization of jointed rock near fracture intersections, through the process often referred to as natural back stoping. There may have been still other processes of breccia formation. The mineralization that followed the brecciation depended on the chance connection of the bottom of the pipe with a channel for mineralizing solutions.

One last instance was most illuminating in its emphasis on our ignorance of the origin of breccia ore. This material consisted of perfectly angular slivers or fragments of highly silicious, barren fine-grained crystalline rock, cemented by pyrite, chalcopyrite, and bornite, with knife-edge contacts between fragments and cementing material. The fragments were from an inch to several inches long, and formed about half of the mass. This rich ore was not in a great fracture zone, or in the vent formed by a volcanic explosion. It should not be called "breccia" at all, if heed is given to the derivation of the word meaning "broken." For it was in the peaceful bottom of an old reverberatory furnace. In the 15 years of operation the quiet bath of matte had eaten its way down many feet into the evenly packed silica floor of the furnace. Instead of replacing the material evenly, or gradually working inward from the edges of the original silica bricks, the matte must have eaten its way along invisible cracks or strain lines, with no rounding or impregnation of the small fragments that remained. Due perhaps to slow cooling, mixed sulphides were deposited instead of solid matte. There was nothing to show what had happened to the silica that had been replaced by the sulphides. Perhaps it had risen through the matte into the slag. Anyhow, it had disappeared.

This furnace-bottom ore proved that no motion, or fracturing, or even any great strain is necessary to form breccia. Nature evidently loves a breccia, and if no violent phenomenon is available, the breccia is formed just the same.

Epigenetic Veins.

Three examinations I made in recent years emphasized the contrast between orebodies that at first seemed to be of the same type—epigenetic veins of complex ores in volcanic rocks. One was in the San Juan Mountains in Colorado, one in Chihuahua, Mexico, and one in the Philippines. In all three the ore consisted of dense, often chalcedonic quartz, part of which replaced

andesite, with calcite and banded sulphides—pyrite, chalcopyrite, galena and sphalerite. The ore contained a few ounces of silver and a fraction of an ounce of gold. The ratio of content of the different metals was closely similar in the three widely separated districts. Specimens of ore from the three mines looked identical.

The only marked difference was the fact that in the San Juan there had been a comparatively rich gold and silver zone on upper levels, while in the other two mines the lean complex ore came to within a short distance of the surface.

In the mine in the San Juan, ore has been developed for nearly 2,000 feet vertically below the bottom of the gold-silver horizon with no important change in grade or character save for a few leaner bands where the dip flattened. This promised well for continuity in depth of the other mines. But the hope was disappointed. In the mine in the Philippines the ore proved to have only 200 or 300 feet vertical extent. At the top, the orebodies that did not actually outcrop passed upward into iron stained shear zones with narrow quartz and calcite stringers, and with hardly more than traces of base or precious metals. At the bottom of the orebodies, the fissures became weaker, and the quartz and calcite, as well as the sulphides, faded away until it was hard to tell whether or not a drift was on the vein. Though only a few of many orebodies have been completely developed the pattern seems unhappily clear.

In the Chihuahua mine a completely different change took place in depth. About 200 meters below the surface the dense quartz and sulphide vein material became thoroughly shattered. Angular fragments of ore were partly or wholly encased in barren botryoidal chalcedony. While the ore fragments were of normal grade, the dilution with chalcedony made most of the material too lean to mine. There were large openings between fragments. A flow of several thousand gallons of water a minute through this open vein material, added to the lower metal content, threatened the existence of the mine.

A study of all the exposed wall rocks failed to disclose any later fault or fracture zone that had shattered the vein and permitted the ingress of solutions that deposited only chalcedonic quartz. It seemed unlikely that the change was due to zoning. The hope for the mine lay in the possibility that a flatter shear zone that was not exposed in the mine or on surface had crushed the vein through a limited vertical extent, and that the chalcedonic silica was confined to the area where this fracturing had cut the vein. If this were true, normal ore with less water might be found at greater depth.

These three examples show how dangerous it is to try to generalize even in the comparatively simple epigenetic orebodies in volcanic rocks. Every district or orebody is a rule in itself.

Fluorspar Mantos.

Sometimes, of course, a resemblance in type of occurrence is of great assistance in finding orebodies that are in most respects completely different. Some of the fluorspar orebodies in Illinois and Kentucky are a good example. A hasty visit to the Cave-in-Rock mines in Illinois gave the curious feeling of having been there before that is often met with in dreams. After some

puzzling, the reason for the feeling came to me. The large, flattened cigar shaped stopes in the Cave-in-Rock fluorspar mines were exactly like those I had seen many years before in the lead-zinc "manto" type orebodies in Chihuahua. Mineralogically they were as far apart as they were geographically, but the shape of the orebodies was the same. A well marked small fault formed one wall of the orebodies, and ore was thickest near this fault. Away from it the ore feathered down to a few inches in thickness, and then played out entirely. Both in Chihuahua and in Illinois the width of ore was ten or more times the maximum thickness, and the length was ten to twenty or more times the width. Faint fractures or joint planes parallel with the long axis could be seen in the flat-dipping limestone roof in both areas. In higher beds —limestone in Chihuahua and sandstone in Illinois—the fracturing or jointing was so slight that it could hardly be recognized. In fact, in Chihuahua the fracturing is so faint that Basil Prescott, and some others who have been successful in developing manto orebodies, think the longitudinal fractures have no importance at all.

On the chance that slight shearing in overlying sandstone might be a clue to other mantos of fluorspar ore in the Kentucky-Illinois field, a search was made for zones of fracturing that had great longitudinal extent, no matter how slight the fracturing. Several zones seemed promising, particularly because the most favorable horizon was within easy reach by drilling. The fact that no fluorspar, and hardly more than traces of calcite, could be found along the fractures on surface was only mildly disappointing. Drilling followed, and in a short time several beautiful examples of manto-type fluorspar orebodies were developed. The resemblance in physical occurrence to the Chihuahua orebodies proved to be the essential character, in spite of the widely different mineralization.

To offset occasional successes of this sort, Nature makes sure that we do not get too confident. After the first few orebodies had been found in Kentucky, drilling of several other shear zones at least as promising as those over the manto orebodies found no ore at all. Local physical conditions were just as favorable, but evidently a channel to the source of fluorspar mineralization was missing. Geologists of the future may find the clue to a complete solution of the puzzle instead of a partial one that is successful only now and then.

CONCLUSION.

These are only a few of the many exciting and varied phenomena that have made my years of examining geology so interesting, and only a few of the many unsolved problems they suggest. I hope they may help to show that hasty visits to many mines may constitute a useful supplement to the detailed study of a few. The most emphatic conviction that has come from my experience is that Economic Geology is still very young. For a long time to come our theories of ore deposition will continue to be uncertain hypotheses, that may be torn down any day by new ideas or new evidence. Sometimes this destruction of older ideas may seem discouraging. But each new theory should be a little less faulty than the last, and each one should help us to find more ore before it proves to be inadequate. Meanwhile, the uncertainties of a

profession that is still rather an art than a science will keep us from becoming conceited—or bored.

There are so many geological mysteries to think about, and so many bouts between Nature and the Imagination, in which Nature almost always comes out on top! Often I wake up in the early morning and wonder at the parade of interesting people and ideas and mines that passes by in our geologic world. And so

> "I thinks about the things that was
> . . . .
> And tells them over to myself
> And sometimes wonders if they're true.
> For they was odd—most awful odd—
> But just the same, now they are o'er
> There must be 'eaps of plenty such
> And if I wait I'll see some more."

San Francisco, Calif.,
Dec. 3, 1951.

SPECTROGRAPHIC STUDIES OF PYRITE IN SOME EASTERN CANADIAN GOLD MINES.

J. E. HAWLEY.

ABSTRACT.

Spectrographic studies of the minor element content of over 200 samples of pyrite in gold bearing quartz vein and replacement deposits in Quebec and Ontario have been made to determine, if possible, any distinctive trends with depth, and to acquire basic geochemical data on pyrite in such occurrences. The deposits included the rather simple quartz vein of the Powell Rouyn gold mine, Quebec, opened to the 2,450 level, the flow-type ore of the Kerr Addison mine, Ontario, extending to the 2,500-foot level, seven mines of the Kirkland Lake gold belt, Ontario, covering a length of about three miles and a depth of over 5,000 feet, and one of the major deposits in the Porcupine gold district, Ontario, to a depth of 5,375 feet.

The studies included conventional direct current arc methods using different techniques, but standardized conditions for samples from individual deposits. Results are presented in log intensity ratios of minor element line vs suitable iron lines as internal standards. Quantitative methods were used for the determination of percentages of cobalt and nickel.

Aside from the variable of depth of occurrence, other factors were also investigated such as size of grain, host rock or matrix, temperature readings as established electrically by Dr. F. G. Smith, University of Toronto, as well as occurrence in different ore bodies or veins of one mine, or in different mines of the one mineralized belt. In the Porcupine area, relation of composition to proximity to, or distance from quartz porphyry contacts was also studied. Trace elements studied included Au, Ag, Te, Ni, Co, Pb, Zn, Sn, Mo, Mn, Cr, Ti, V, Bi, and As. Some characteristic differences in trace elements in the different deposits are noted, as are variations which may be related to the several factors studied.

Cobalt and nickel both range from 0.02 to 0.10 percent, and in most the ratio of Co: Ni is about 1: 2. Kirkland Lake pyrite contains more of both than the others while pyrite from Porcupine, giving only low temperature readings, contains less.

The only persistent variation in composition of pyrite with depth is an increase in cobalt, and, though locally other variations are of interest, the relative uniformity of conditions of mineralization to depths of over 5,000 feet is emphasized.

Spectrographic studies of pyrite giving high and low temperature effects by methods employed by Smith, confirm differences in conditions of deposition, particularly by their content of cobalt, nickel, and arsenic. All types of pyrite of these deposits are believed to have been deposited with at least trace amounts of gold, and to have been enriched by a later introduction. Such later introductions cannot be related clearly to low-temperature readings, but are believed controlled to a greater extent by original and imposed structural factors rather than original temperature of deposition of the pyrite.

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INTRODUCTION.

DURING the past three years spectrographic studies have been made of pyrite associated with gold-quartz veins and replacement deposits in four different localities in Eastern Canada with the chief purpose of determining whether or not variations in trace elements would give any indication of significant changes

in grade of ore with depth, a problem on which attention has been focussed by L. C. Graton's contribution to the Report of the Committee on Research on Ore Deposits of the Society of Economic Geologists (12).[1] At the same time it was hoped to add to the rather meager basic geochemical data available on pyrite and some other minerals in these deposits. Two of the studies were integrated with other research, one, on specimens from the Porcupine District of Ontario on which temperature determinations had been made by Dr. F. G. Smith (21), University of Toronto, and the other on collections made by Dr. J. E. Thomson (24), Ontario Department of Mines, in connection with his geological study of the several mines in the Kirkland Lake gold belt, and the detailed mineralogy of the ores, by the present author. These two investigations included pyrite of ores extending to depths of 5,375 and 6,150 feet, respectively. In addition, less involved studies have been made of pyrite from certain ore bodies of the Kerr Addison mine of the Larder Lake District, Ontario, and of the Powell Rouyn Gold Mine, Noranda District, Quebec, both covering a vertical range of some 2,500 feet.

Review of Literature.—Auger (3) initiated spectrographic studies of this type on pyrite of various Canadian gold deposits including some with which base metals are associated, and called attention to the possible use of spectrographic methods in attempting to solve problems in economic geology. Some of his results are confirmed by the present investigation but others require modification.

About the same time and in succeeding years the cobalt, nickel, manganese, and zinc content of pyrite and associated sulfides, pyrrhotite, and chalcopyrite, has been investigated by various authors in Norway and Germany, including Carstens (6, 7, 8), Hegemann (13, 14), Bjørlykke (5, 6), and Gavelin and Gabrielson (11).

These deal chiefly with range of concentration of the minor elements mentioned in pyrite, the manner in which they are present in the lattice, and variations in composition of pyrite from ores of different origin and in different wall rocks. Further discussion of some of their findings are given in appropriate places in this paper.

Acknowledgments.—Grateful acknowledgment is made to the Research Council of Ontario for grants in aid of research from which costs of both spectrographic equipment and technical services have been met.

For collections of specimens the writer is indebted to the following: Dr. J. E. Thomson, for material from most of the mines at Kirkland Lake, Dr. G. H. Charlewood, Lake Shore Mines Limited; Dr. F. G. Smith, for specimens from the Porcupine District, Ontario; J. W. Baker, Kerr Addison Gold Mines, Ontario, and to Mr. J. E. Jerome and Dr. R. C. McMurchy, Powell Rouyn Gold Mine, Quebec.

Technical assistance in both preparation of samples and spectrographic analyses has been rendered from time to time by S. C. Robinson (1948), W. J. Wark (1948–50), and more extensively by Miss Y. Rimsaite (1949–50). To Dr. Michael Fleischer, the writer is indebted for various references on spectrochemical investigations of pyrite.

[1] Numbers in parentheses refer to Bibliography at end of paper.

Spectrographic Methods.—1. Preparation of samples—In all cases pyrite was hand picked with the aid of a binocular microscope from ore samples crushed to minus 40 mesh. Recovered pyrite was then finely ground in an agate mortar and when purification from gangue minerals was necessary, this was carried out in separatory funnels with bromoform. In one case a Haultain super-panner was used. Polished sections of ore specimens comparable with those crushed were made in order to ascertain the relationship of pyrite to other minerals. These are described under the various ores studied.

2. Spectrographic techniques—DC arc methods were used for spectrographic analysis of all samples, but methods of sample preparation varied in some cases. In the earlier work on pyrite from the Kirkland Lake Mines, 5 mg samples of − 200 mesh pyrite were transferred to shallow (1/10″ deep) crater high-purity graphite electrodes on the top of which 5 mg graphite was packed. Analyses were carried out on a 2 m spectrograph with a grating of 24,400 lines per inch. A dc arc of 9.5 amps; 300 v was used across a 4 mm gap. Spectra over the range 2,200 Å–4,800 Å were investigated, the lines being recorded in most cases on Spectrum Analysis Film No. 2, on the basis of the uniform gamma it possesses over this range. For each sample two uninterrupted exposures were made, one of 15 sec for the more volatile elements and a second of 25 sec for the less volatile.

Resulting spectra were identified by means of a master film mounted in a comparator-densitometer, and transmission values for required lines were measured and intensity ratios calculated from characteristic curves. Film calibration was made with two-step filters at about 3,200 Å.

Analysis lines were selected on a basis of intensity, sensitivity, and freedom from interference. As internal standards, suitable iron lines were used because of the relative constancy of this element as a major constituent.

For a special suite from the Lake Shore mine at Kirkland Lake, and in all the other analyses reported, samples were compressed on flat-topped short (1 cm) lengths of grade I graphite electrodes to form pellets as described by Wark (25). These were placed in brass electrode holders and may be either arced or sparked against a hemispherical-tipped counter electrode. Sample weights used varied in different suites of samples, from 10 mg (Lake Shore suite), to 2 mg in the case of samples from the Porcupine District, Kerr Addison, and the Powell Rouyn mines. For the pellet method, exposures were varied from 10 to 45 seconds across a 3 mm gap. Depending on the density of the lines sought in different samples variable transmissions of 3, 6, 12, and 25 percent were obtained by a combination of an adjustable intensity control stand and a set of two step filters(within the camera), transmission values of the latter varying 50 percent. With the two step filters as lines of elements present in higher concentrations become too dense for determination of transmission values, that portion of the spectra which had been filtered an additional 50 percent, was read and comparable intensity ratios calculated.

For any one suite of samples spectrographic conditions were constant so that comparison may be made of intensity ratios within each group but not of results of one deposit with another, which is perhaps unfortunate, though this was not the main purpose of the investigation.

Photographic procedures followed the conventional methods and again were constant for each suite of specimens.

Elements studied included Au, Ag, As, Ni, Co, Mn, Mo, Pb, Sn, V, Ti, and in some ores also Ba, Sr, Te, and Bi. Only in the case of Co and Ni were actual quantitative determinations made and the results given in the following tables are comparative log intensity ratios for line pairs noted, use of which is restricted to ratios of any one element in a given suite of pyrite determined under the conditions specified. In other words, the results so stated show comparable variations in any one element of pyrite occurring at different levels, in different matrices or of variable grain size, but not the actual amount of that element.

Reproducibility of Intensity Ratios.—The advantages of the pellet method of sample preparation in the case of pyrite is well shown by results obtained on a suite of samples supplied by Lake Shore Gold Mines. Five samples of each of fourteen specimens of pyrite were analyzed by DC arc methods in the pellet form using both Spectrum Analysis No. 1 and No. 2 type film. Reproducibility tests on the line pair Co-3049.0/Fe-3014.1 in 14 samples using five different films gave an average percentage deviation of intensity ratios of 4.4 percent (Wark, 25). This is better than the usual deviation of 10 percent obtained in much DC arc work with open crater electrodes and it has the further advantage of avoiding frequent loss of sample when it has attained a molten bead form during arcing.

Quantitative Determination of Nickel and Cobalt in Pyrite.—For the quantitative determination of nickel and cobalt in pyrite, standards were prepared from a sample of pyrite showing no traces of nickel or cobalt. After fine grinding this was mixed with spectrographically pure nickel oxide and cobalt oxide (Co_3O_4) so as to yield two sets of standards containing from .003 to 0.1 percent nickel and cobalt, respectively. Two sets of each standard, containing 2 and 5 milligrams pyrite in weight were made. The 5 mg samples were mixed with an equal weight of high purity briquetting graphite and compressed in pellets as described above. The 2 mg samples were not diluted and gave a lighter background. These were arced against a hemispherical tipped counter electrode with the following conditions:

Time—45 sec for 5 mg samples.
10 sec for 2 mg samples.
Current—DC arc— 5 amps–300 v for 5 mg samples.
11 amps–300 v for 2 mg samples.
Gap and slit—3 mm–40 microns.
Transmission— 6% for 5 mg samples—with 2 step filters at 3400–3500A° (6% and 3%).
12% for 2 mg samples—with 2 step filters as above (12% and 6%).
Film—Spectrum Analysis No. 2.
Photographic—Develop 5 min D19, Stop bath 30 sec.
Fix 10 min, Wash 10 min, Dry 2.5 min.
Line pairs—Ni 3414.76/Fe 3401.52.
Co 3453.50/Fe 3458.30 (only in absence of Ni).
Co 3453.50/Fe 3401.52 (in presence of Ni).
Co 3405.12/Fe 3401.52.

Average log intensity ratios were determined on samples of each standard for the line pairs given, and plotted against composition. Figure 1 is an example of working curves developed in this manner for 5 mg samples. All samples of pyrite were then prepared in an identical manner and analyzed under similar spectrographic conditions.

Line Pairs.—Table I gives a list of line pairs used in this work after careful checking for interference from other elements. For each element the most commonly used line pair is given first, and others later. For cases in which the more sensitive lines were too dense to be determined photometrically, less

TABLE I.

LINE PAIRS.

Element	Wave length	Iron	Wave length	Absolute sensitivity
Ag	3280.68 3382.89	Fe	3325.46 2675.28 2675.28	.0001–.00003%
As	2780.19	Fe	2778.84	.01%
Au	2675.95 2427.95	Fe	2675.28 2675.28	.001%
Ba	4554.04	Fe	4607.65	.001–.0001%
Bi	3067.71	Fe	3068.17	.001%
Co	3405.12 3453.50 3395.37 3048.88	Fe	3401.52 3458.30 3396.97 3014.17	.0002%
Cr	4254.34 4274.80	Fe	4255.49 4285.44	.0001%
Mn	2798.27	Fe	2778.84	.0005–.0001
Mo	3170.34	Fe	3172.06	.00001%
Ni	3414.76 3320.25	Fe	3401.52 3303.56	.0002%
Pb	2833.06	Fe	2778.84	.00002%
Sn	3175.01	Fe	3172.06	.001%
Sr	4607.33	Fe	4613.21 4607.65	.001–.0001
Te	2385.76	Fe	2675.28	.01%
Ti	2956.13 3387.83	Fe	2954.65 3392.31	.0001%
V	3185.39 4379.23	Fe	3172.06	.001–.0005
Zn	3282.33	Fe	3325.46	.01%

sensitive lines were used in order to obtain results on as many elements as possible with one type of exposure.

Character and Composition of Pyrite Studied.—The value of any spectrographic analyses of pyrite must depend on its relative purity and freedom from inclusions of other minerals. In all cases, therefore, microscopic study was made of polished sections of typical samples, in order to determine the general characteristics of the pyrite and the nature of inclusions which are almost invariably present.

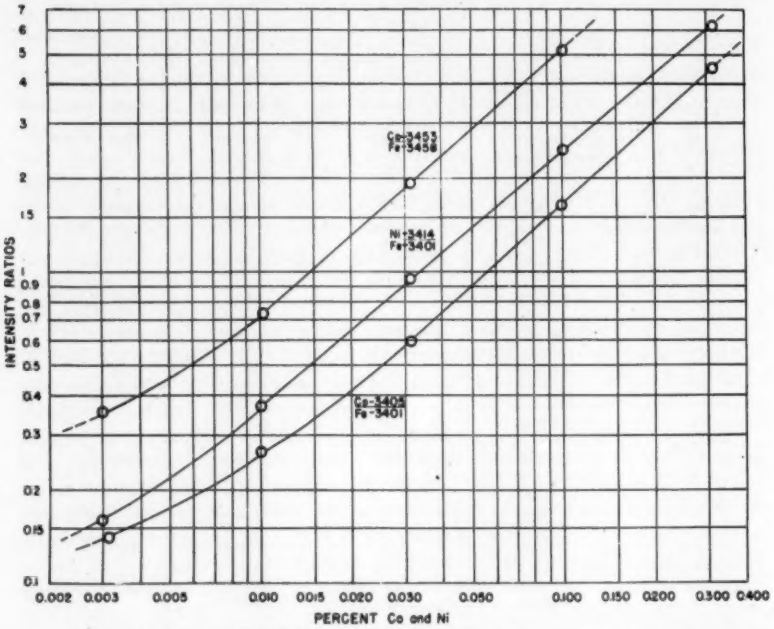

FIG. 1. Working curve for the quantitative determination of cobalt and nickel in pyrite (5 mg samples on pellets, 45 second exposure, DC arc 5 amps. Kerr Addison Pyrite 11).

In the four deposits under investigation both hand specimens and polished sections show very clearly that in most places gold and alloyed silver have been deposited separately from the pyrite and occur both in other minerals, such as quartz, and encrust or fill fractures in or irregularly replace pyrite. In some pyrite, notably from Kirkland Lake and more rarely from Porcupine, irregular blebs of gold occur in the pyrite (higher temperature type) without any related visible fractures. (Such occurrences may be due either to contemporaneous deposition of gold in pyrite or replacement along concealed ducts.) Since

it is clearly impossible to section and examine every grain of pyrite used for analysis, it is obviously impossible to state exactly the origin of *all* the gold (and silver) or to differentiate always between that which has been deposited contemporaneously with the pyrite and that introduced at a later time. None-theless in some cases (Porcupine District) as shown later, certain distinctions can be drawn.

In all cases pyrite picked for analysis has been chiefly that with which no visible late gold was associated. In a few cases where this was not possible, only that part of the pyrite, apparently free from gold, was selected. In practically all cases, however, gold and silver were found in sufficient quantity to give distinctive spectra, even from localities somewhat removed from actual ore bodies, and it is believed that in such cases, where relatively low intensity ratios are given, much of this represents gold deposited contemporaneously with the pyrite as otherwise much barren pyrite should have been found. This is particularly the case with many of the specimens from the Powell Rouyn pyrite and the Kerr Addison flow type pyrite. It seems also true in both the Kirkland Lake and Porcupine areas though in these much visible gold is associated with the ores.

Where extremely high intensity ratios of gold or silver were found in pyrite it is probable much of this is to be accounted for by its later introduction, though it should be noted high silver ratios are not always accompanied by high gold, in which instance silver must be accounted for in some other way.

Of the other minor elements studied in pyrite, as noted by Auger (3) and others, Co and Ni are sufficiently closely related to iron in atomic radius to substitute easily for iron in the pyrite lattice in the small amounts found. Hegemann (14), however, is of the opinion that neither Mn nor Zn can replace Fe in the lattice of pyrite to any great extent, and that cobalt and nickel are somewhat similarly restricted though amounts found range up to 0.1% to 0.2% Co and up to 0.55% Ni, amounts which are greater than recorded in most Canadian pyrite.

The manner of occurrence of Pb, Zn, Sn, and Mo is not known. The first two and possibly Mo, may be accounted for perhaps by minute inclusions of the common sulfides which are known to be present in some of these deposits, though judging by the relatively constant intensity ratios all are believed more likely present, if not in true substitutional solid solution, as impurities along discontinuities or vacant spaces within the pyrite lattice.

Cr, Mn, and V may in part be accounted for by inclusions of wall rock minerals, and titanium, particularly in the Kirkland Lake pyrite, is almost certainly inherited from replaced graphic intergrowths of magnetite-ilmenite, remnants of which may still be found.

PYRITE FROM POWELL-ROUYN QUARTZ VEIN, QUEBEC.

The Powell Rouyn quartz vein affords an excellent example of a rather simple fracture filling in relatively uniform wall rocks, and hence was chosen as a test case for study of variations in minor element content with depth.

This deposit is described by McMurchy (18a). It lies in a granite mass, 2 miles northwest of Noranda, Quebec, and consists of a quartz vein striking

N 30°W and dipping 55° to 75° E. which has been explored to a depth of 2,450 feet. A sheared basic dike fills the same fracture and is pre-ore. In places there are two or more parallel veins and dikes for short distances along the strike. The main vein has a maximum length of about 600 feet.

For the most part the vein consists of massive quartz sparingly mineralized with pyrite, chalcopyrite, and some specular hematite. Average sulfide content is about 3 percent. Visible gold is rare in the deposit as a whole, but does occur in high-grade sections and much becomes visible on crushing. The coarser disseminated pyrite in the quartz is auriferous and is considered by McMurchy to represent a first period of mineralization that was followed by a later injection of finer pyrite, chalcopyrite, specularite, and additional gold. Tellurides are very rare but tetradymite has been identified. Some later faulting has occurred with introduction of calcite and ankerite. Granite wall rocks are silicified and in places mineralized with pyrite.

Nineteen samples of pyrite from the 200- to 2,450-foot levels were analyzed under conditions noted below. Of these only one (PR-11) was from a cross vein that is apparently later in age than the main vein and contains some visible gold. All others were from comparable localities in the main vein.

Polished sections of high-grade ore show pyrite in hypidiomorphic cubic and pyritohedral forms in quartz which here and there carries whisps of specularite or magnetite. Both quartz and magnetite appear to replace and embay the pyrite. Chalcopyrite, and more rarely gold, occur within grains of pyrite, apparently unrelated to any visible fractures, but both minerals are more abundant filling well-defined fractures, cutting and replacing to some extent both quartz and pyrite. Most of the gold is thus clearly later in age than the pyrite. Very minute grains of a white isotropic mineral, likely a telluride, are locally associated with the gold.

Spectrographic Conditions.—

2 mg pyrite pellets—10 second exposures.
DC arc, 11 amps. Transmission 12% except for Co, Ni, Ag, — 6%.
3 mm Gap. Film Type S.A. No. 2.

Each sample was run in triplicate and the intensity ratios for twelve line pairs were determined and averaged. Actual percentage of cobalt and nickel were determined from prepared working curves.

The results are given in Table II along with average pyrite goethermometer readings made by Dr. F. G. Smith [2] and A. D. Mutch on ten samples.

Discussion of Results.—Minor elements in the pyrite in sufficient concentration to allow study of their variations consist of gold, silver, bismuth, chromium, manganese, lead, molybdenum, tin, vanadium, zinc, cobalt, and nickel. Titanium is present in greater amounts in samples 8, 9, and 12, but was not determined in others. Arsenic was not detected in any samples.

Temperature effects detected by Smith suggest rather uniform temperature conditions during deposition and, in this case, that there was no considerable difference in this respect between fine and coarse pyrite (as in PR-13a and 13b) nor between early and late depositions (*cf.* PR-10 and 11).

[2] Personal communication.

TABLE II.

INTENSITY RATIOS—POWELL-ROUYN PYRITE WITH PERCENTAGES OF COBALT AND NICKEL.

No.	Depth	Aver. temp. reading	Description	Au	Ag	Bi	Cr	Mn	Pb	Mo	Sn	V	Zn	%Co	%Ni
PR −1†	200′	426° C	Coarse	2.74	2.90	.44	1.07	.68	.53	.56	.72	.40	.35	.006	.009
−2	350		Med. cubes tarn.	6.82	3.44	.34	.92	.64	.21	.60	.64	.34	.22	.0014	.008
−3	500		Massive	6.25	3.61	1.41	.71	.65	.75	.59	.66	.40	.31	.0052	.0098
−4	650		Small cubes V.G.	9.50	5.00	1.85	.75	.24	1.04	.50	.64	.32	.37	.0098	.026
−5	800		Small cubes V.G.	5.95	4.00	1.70	.73	.23	.97	.39	.63	.30	.34	.0190	.055
−6	950		Small cubes V.G.	5.72	3.50	1.25	.65	.24	.93	.40	.68	.25	.34	.0120	.040
−7	1,100	482° C	3 mm cube V.G.	7.35	3.00	1.00	.90	.19	1.06	.46	.63	.32	.36	.0220	.064
−8	1,250		Fine	1.27	1.77	tr	11.00	.66	.29	2.12	.82	.47	.79	.0270	.040
−9	1,400		Fine	.92	.69	tr	.66	.63	.31	1.01	.66	.35	.38	.009	.027
−10	1,550	473	Coarse, V.G.	8.50	3.00	1.00	.76	.37	.32	.42	.65	.33	.31	.038	.10
−11	1,550	471	Cross vein	.54	.13	.78	.77	.21	.21	.43	.64	.29	.34	.035	.10
−12	1,700		Fine	2.59	2.31	.39	9.00	.62	.31	5.50*	.86	.40	.36	.071	.082
−13a	1,850	486	Fine + 1 mm V.G.	14.35	4.90	.29	.78	.38	.32	1.04	2.18	.43	.81	.0245	.067
−13b†	1,850	486	Coarse	2.01	2.69	1.20	.72	.18	1.13	.47	.62	.31	.25	.0115	.047
−14	2,000	486	Coarse tarn.	.59	.24	tr	.64	.17	.27	.46	.61	.29	.21	.004	.0074
−15	2,150	520	Highgrade V.G.	2.73	2.28	.90	.65	.20	.63	.45	.62	.29	.18	.001	.0053
−16	2,150	488	Coarse	6.55	2.60	.80	.64	.21	.64	.40	.61	.28	.14	.007	.062
−17	2,300		Coarse	4.18	4.00	1.50	.84	.23	.99	.53	.66	.35	.26	.0054	.0055
−18	2,450	485	Coarse and fine	6.00	4.05	.45	1.04	.28	.22	.51	.68	.39	.27	.10	.080
	200–1,400′		Average	5.17	3.10	.89	.80	.46	.68	.74	.67	.35	.39	.0102	.031
	1,550–2,450		Average	4.80	2.62	.73	.76	.26	.51	.61	.67	.34	.31	.0297	.0556

* Erratic changed to average of 0.89.
†Assay of combined pyrite from sample PR −1 and 13b gave 14 ozs. Au, 10 oz. Ag, 0.04 oz. Bi/ton.
V.G.—Visible gold in original sample.

The wide variation shown in intensity ratios of gold, with, in some cases, a sympathetic variation in silver, is clearly a reflection of the fact that some gold is present in discrete particles within the pyrite rather than being uniformly and finely disseminated or in solid solution. Variations vertically, while not outstandingly evident, are shown in the table by averaging ratios (or percentages) between surface and the 1,400 level and from the 1,550 to 2,450 levels. These show a decrease vertically in gold and silver, both of which are difficult to evaluate due to the presence of visible gold. Smaller decreases are noted in Bi, Cr, Pb, Mo, a more marked decrease in manganese, an increase in both cobalt and nickel, but no change in either tin or vanadium with depth.

Overall averages of cobalt and nickel are, respectively, .02 and .04 percent, with a ratio of Co to Ni of 1 : 2.

Average analysis of fine grained samples compared with that of five coarse grained pyrites show the coarser material is higher in Ag, Bi, and Pb; gold is the same in both, but the fine grained is appreciably higher in Co, Cr, Mo, and Sn, despite rather similar temperature determinations.

The vertical variations are somewhat different from those found in other pyrites studied by us as summarized later, and in pyrite in the nearby Noranda massive, sulfide deposits where Auger (3, p. 417) noted a downward increase in both silver and vanadium, a distinct decrease in cobalt, a slight decrease in zinc while lead and nickel remain fairly constant.

PYRITE FROM KERR ADDISON GOLD MINE, ONTARIO.

Some forty odd specimens of mineralized "flow" ore, covering a vertical range from 700 to 2,500 feet below surface were obtained for study from the Kerr Addison Gold Mine through the kindness of J. W. Baker, Chief Geologist. These are chiefly from No. 21 ore body but a few are representative of ore bodies No. 16 and 17.

The geology of the mine is described by J. E. Thomson (23) and more recently by the staff of Kerr Addison Gold Mines (1951).

The Kerr Addison deposit is now one of Canada's most important gold producers. Some eighteen ore bodies are present in the complex carbonated and schistose fault zone, known as the Larder Lake Break. Ore bodies are of two types, those in carbonate zones and others in tuffs and volcanic flows, both believed to be contemporaneous but differing in character with the host rock. Samples of ore studied spectrographically are limited to the flow type. These are described as showing considerable pyrite mineralization with traces of chalcopyrite, galena, sphalerite, scheelite, and arsenopyrite. Most of such ore is in lavas rather than tuffs. The pyrite is noted as carrying gold but rarely, coarse visible gold is also found associated with black quartz stringers. Two ages of pyrite are indicated, the earlier carrying "negligible values but the later consistent values."

Of interest also in this study is the persistence of ore-making features of this deposit with depth, as described by the Staff (p. 75). Both faults and fold structures to which ore deposition is closely related show no evident change down to the 2,650 level at present under development. "The character

of the alteration and ore deposition has remained unchanged though the percentage of sulfides in the flow-type ore has shown a tendency to increase with depth."

Concentration of Pyrite.—Ore samples were crushed and the sulfides concentrated in a Haultain superpanner. Pyrite tailing was recovered, dried, and a magnetic fraction, chiefly magnetite, removed. The concentrate was then finely ground in an agate mortar and made up into pellets, as noted above, using 5 mg pyrite to 5 mg briquetting graphite. Hemispherical tipped pellets and similarly shaped graphite counter electrodes were used.

Spectrographic Conditions.—

D.C. arc, 5 amps, 300 v on short circuit.
Gap—3 mm. Slit—40 u.
Transmission—For Co and Ni—3%.
For Au, Ag, Ti—6%.
For other trace elements—25%.
Film type—Spectrum analysis No. 2.

By use of filters in an intensity control stand, transmission is set at 6 or 25 percent as above. In addition, by introducing a two-step filter, cobalt, nickel, and iron lines can be read at either 3 or 6 percent transmission depending on the density of the respective line pairs.

Three analyses were made for each sample and the results averaged, except for the minor trace elements, where three runs were made on all samples from No. 21 ore body varying the current from 5 to 11 amperes and using spectrum analysis Film No. 1 as well as No. 2. Film type No. 1 with 25 percent transmission was found preferrable for elements present in minute traces since it gave much lower background readings.

Variation in Minor Elements in Pyrite with Size of Grain, Host Rock, and Temperature Recordings.—In cooperation with Dr. F. G. Smith variations in the trace elements in pyrite from two localities in this deposit were studied in relation both to size of grain, host rock, and temperature effects detected with the pyrite geothermometer.

Table III gives results of spectrographic analyses of different types of pyrite from a single ore specimen from the 2,500 level. In this, coarser, striated, cubes (+ 1 mm dia.) of pyrite are disseminated in a ½ inch wide quartz vein (type 1); smaller, 1–0.1 mm dia. cubes are disseminated in gray siliceous flow rock, type 2, and very fine pyrite (< 0.1 mm dia.) occurs in very narrow seams within the wall rock, or along the contact with the quartz vein, type 3. Both the coarser pyrite in quartz and finer cubes within wall rock, according to Smith, show the same temperature at 290° ± 20° C suggesting contemporaneity of formation. The fine pyrite No. 3 was considered by Smith as too fine-grained for a reliable temperature determination, but when in electrical contact gave a reading at 400° C.

A comparison of intensity ratios for various elements studied, Table III, suggests rather wide variations in all except those present in small traces. Gold and silver are distinctly highest in the very fine-grained pyrite, but otherwise this pyrite, though showing a doubtful temperature reading at 400° C compared with 290° C for the others, shows only minor differences in content

of most of the other elements compared with the coarser wall-rock pyrite. Both types of pyrite in wall rock (2 and 3) show decidedly higher titanium and zinc and somewhat lower nickel, than pyrite in quartz. The difference in titanium may be attributed to the wall rock but no explanation can be offered for differences in zinc and nickel. It may also be noted here that high gold and silver ratios in this deposit are not related to a similar ratio of arsenic as in pyrite from the Porcupine area (see p. 290). Compositional differences which might be related to temperature or size of grain are discussed after a second set of examples are given.

TABLE III.

SPECTROGRAPHIC ANALYSES OF PYRITE.
(Specimen KA 43, ore body 21, 2,500 elevation.)

	Intensity ratios		
	1	2	3
	Pyrite in quartz	Small cubes in wall rock	Very fine pyrite in wall rock
Temp. reading	290° ± 20° C	290° ± 20° C	400° C (doubtful)
Au	2.02	2.95	4.78
Ag	1.72	2.32	6.12
Ti	.19	2.35	2.21
Co	.583	.438	.447
Ni	1.80	.481	.617
As	.36	.445	.35
Mn	.88	.64	1.31
Pb	1.14	1.00	.46
Mo	.66	.65	.55
Sn	.83	.72	.61
V	.56	.76	1.17
Zn	.52	1.32	1.04

Spectrographic conditions. DC arc, 5 amp, Exp. 45 sec on 5 mg samples in pellets with 5 mg graphite.
Transmission 3 and 6% for Au, Ag, Ti, Co, Ni, 25% for others.

Two other specimens, supplied by Smith, were studied in a similar manner. These consist of pyrite (1) from a barren vein intersected by a 2,500 cross-cut into the Arjon property (hence not comparable with sample KA 43 from No. 21 ore body). This gave temperature readings at 450° ± 50° C and a few low ones at 175° C, suggesting to Smith[3] that it represents early high-temperature pyrite little modified by later gold-bearing solutions which might have been introduced at the lower temperature noted. A second specimen came from high-grade flow type ore on the 1,100 level. This contains slightly coarser pyrite (2) in quartz stringers, yielding readings identical with the specimen from the 2,500 cross-cut, and somewhat finer pyrite (3) in the

[3] Personal communication.

wall rocks, giving temperature readings at 300° C. Spectrographic results, stated in terms of log intensity ratios, are given in Table IV for three types of pyrite noted in these specimens. These show that No. 1 (2,500 level) pyrite is surprisingly similar in content of nickel, lead, molybdenum, tin, vanadium, and zinc to pyrite No. 2 from a quartz vein on the 1,100 level. It differs from both pyrites of the upper level in having a relatively low content of gold and silver. The results tend to confirm Smith's suggestion that both No. 1 and 2 pyrite were of similar origin and that the higher precious metal content in the

TABLE IV.

SPECTROGRAPHIC ANALYSES OF KERR ADDISON PYRITE.
(Specimens F90 49–KA23, and F95 49–KA25.)

	Average intensity ratios		
	1	2	3
	2,500 level Arjon X cut "Barren" vein pyrite	1,100 level coarser pyrite in quartz	1,100 level finer pyrite in wall
Temp. reading	450° ± 50° few 175° C	450° + 50° few 175° C	300° C
Au 2676	.73	Ex	3.0
Ag 3280	.54	Ex	2.38
Ti 2956	.18	—	.19
Co 3405	.30	.18	.64
Ni 3414	.67	.69	1.72
As 2780	.25	.42	.30
Cr 4254	1.06	.65	1.03
Mn 2798	1.1	.65	1.12
Pb 2833	.66	.55	.84
Mo 3170	.44	.40	.52
Sn 3175	.68	.66	1.10
V 3185	.33	.32	.40
Zn 3282	.25	.25	.67

Ex = extreme.

Spectrographic conditions: DC arc, 11 amp, Exp. 10 sec, on 2 mg samples on flat topped pellets. Transmission 12%

These spectrographic settings are varied, compared with settings given in Table III, in order to bring out in all comparable samples, interference free lines of the various elements at a density which may be read with photometric equipment.

one may be due to later introduction. This explanation may also account for higher precious metals noted with the very fine pyrite of spec. 43 (Table II) since its almost pulverent character would afford greater ease of penetration than a more solid crystal.

Comparing No. 2 and 3 from the same specimen, we may note higher gold and silver in pyrite in quartz compared with wall rock, the opposite to the condition noted in a specimen (KA 43) from the 2,500 level Table III, though clearly this may not be of much significance if gold and silver are largely of late origin and have been introduced wherever openings occurred at the right time. Otherwise the wall rock pyrite is higher in most other elements, particularly co-

TABLE V.

Ore body	No. spec.	Intensity ratios			Percentage	
		Au	Ag	Ti	Co	Ni
21	30	1.49	1.09	1.02	.040	.049
16	5	1.65	1.08	.98	.039	.050
17	4	1.84	1.77	.88	.033	.040

balt, nickel, chromium, manganese, and titanium, as might be expected in pyrite formed in part by replacement. No particular effect on composition can be attributed to the somewhat lower temperature readings for pyrite in the wall rock compared with that in quartz. The ratio of Co : Ni (intensity ratio) in both types from the 1,100 level is about 1 : 3.

Variations in Pyrite from Different Ore Bodies (Flow Type) Kerr Addison.—Though the number of specimens available for analyses from three ore bodies of the flow type, Nos. 16, 17, and 21 are widely different, a comparison is afforded for five elements in the pyrite of these in Table V. Figures given for Au, Ag, and Ti are intensity ratios of these elements vs iron lines as internal standards, but for Co and Ni actual percentages are stated.

A further comparison of eight minor elements in pyrite of these ore bodies is given in Table Vb in which intensity ratios were determined by DC arc methods, 5 amps., and 25 percent transmission.

The results given show only minor differences between the different ore bodies as would be expected in the case of ores produced by one general period of mineralization in similar host rocks. The one distinctive difference appears to be the low chromium and higher manganese content of pyrite from No. 17 ore body. This is also lower in cobalt and nickel whereas pyrite in ore bodies 21 and 16 are almost identical in this respect. Pyrite in 16 and 17 ore bodies shows somewhat higher gold and silver ratios than in No. 21, but additional analyses from the former are needed before attaching significance to this fact.

Vertical Variation in Composition of Pyrite—Kerr Addison.—Analyses of 30 samples of pyrite from No. 21 ore body over a vertical range from the 686 to 2,500 levels allow comparisons to be made of vertical variations in composition. Results are given in two tables. Table VI shows variations in intensity

TABLE Vb.

AVERAGE INTENSITY RATIOS IN ORE BODIES.

Ore body	No. samples	Intensity ratios							
		Cr	Mn	Pb	Mo	Sn	V	Zn	As
21	30	.69	.68	.33	.67	.76	.78	.54	.48
16	6	.54	.52	.34	.60	.69	.69	.42	.34
17	3	.28	.72	.45	.72	.73	.83	.56	.39

ratios for Au, Ag, and Ti and in percentages of cobalt and nickel as determined under similar spectrographic conditions noted. Table VII shows variations in other elements present only in traces for which a higher transmission was used.

From Table VI it is readily apparent that both gold and silver show an increase with depth. This is particularly noticeable from the 1,000 to the 2,500 level. Titanium also increases slightly at depth but both cobalt and nickel content here show a decrease in the lower half of the section studied. (See averages for 686 to 1,230 levels and 1,286 to 2,500.)

TABLE VI.

SPECTROGRAPHIC ANALYSES OF PYRITE, ORE BODY NO. 21
KERR ADDISON GOLD MINE.

Depth	No. spec.	Intensity ratios			Percentage	
		Au	Ag	Ti	Co	Ni
686′	1	.90	.36	.93	.028	.034
850	1	.66	.74	1.22	.054	.071
917	1	.85	.74	1.28	.046	.024
986	2	1.21	1.14	.61	.033	.033
1,055	1	.87	.60	.98	.025	.024
1,050	5	1.59	.94	.84	.062	.082
1,207	1	1.61	1.17	.72	.045	.066
1,220	1	1.17	1.00	1.04	.050	.030
1,230	1	1.30	1.20	1.76	.061	.060
1,286	4	1.12	.53	.75	.027	.034
1,450	1	1.12	.67	1.40	.039	.070
1,600	3	1.28	1.04	1.24	.034	.054
1,750	6	1.99	1.57	1.13	.037	.046
1,900	1	3.10	2.00	1.00	.032	.033
2,500	1	2.60	2.50	1.23	.024	.025
Average	30	1.49	1.09	1.02	.040	.049
686–1,230	14	1.27	.91	.95	.049	.056
1,286–2,500	16	1.69	1.24	1.07	.033	.044

Spectrographic conditions—Au, Ag, Ti—5 mg pyrite + 5 mg graphite. Co, Ni— DC arc, 4 amp, Exp. 45 sec., Trans. 6%, Film—S.A. No. 2.

Elements present in lower concentrations are listed in Table VII. Intensity ratios for these (iron as internal standard) show variations from level to level of as much as 50 percent, but the average of 14 samples from the upper half of the mine differs only slightly from that of 16 samples from the lower half. With the exception of zinc which is constant and vanadium which decreases slightly, Cr, Mn, Pb, Mo, Sn, and As all show slightly higher ratios at depth. The differences, however, do not seem sufficiently great to be significant.

Analyses of samples of ore bodies 16 and 17 are not sufficient to allow any certain trend in minor constituents to be determined, but it may be noted that in ore body No. 16, as in No. 21 pyrite from the 2,500 level also shows higher ratios in gold and silver than pyrite from above the 1,000-foot level.

TABLE VII.

VERTICAL VARIATION IN TRACE ELEMENTS IN PYRITE
ORE BODY 21—KERR ADDISON GOLD MINE.
Intensity Ratios.

Depth	No.	Cr	Mn	Pb	Mo	Sn	V	Zn	As
686	1	—	.73	.39	.79	.84	.82	.55	.89
850	1	.62	.37	.26	.54	.69	.73	.93	.25
917	1	.66	.57	.32	.51	.70	.67	.49	.27
986	2	.61	.54	.28	.56	.57	.61	.48	.25
1,055	1	.84	.62	.50	.90	.88	1.05	.67	.60
1,150	5	.79	.72	.28	.70	.76	.83	.50	.49
1,207	1	.60	.33	.23	.61	.76	.64	.36	.25
1,220	1	.57	.83	.41	.80	.85	.97	.70	.43
1,230	1	.39	.50	.35	.48	.55	.92	.45	.46
1,286	4	.80	1.02	.42	.80	.92	.82	.63	.47
1,450	1	.53	.98	.46	.55	.63	.64	.71	.54
1,600	3	.37	.60	.28	.58	.78	.76	.40	.34
1,750	6	.86	.65	.32	.71	.73	.76	.52	.58
1,900	1	1.03	.54	.31	.54	.77	.62	.40	.50
2,500	1	.82	.39	.35	.65	.86	.92	.73	.90
Average Intensity Ratios									
686–1,230	14	.63	.62	.32	.66	.73	.80	.54	.44
1,286–2,500	16	.74	.73	.35	.69	.79	.77	.54	.52

Spectrographic conditions: D.C. arc, 5 amp, 300 v, Exp. 45 sec, Film No. 2, Transmission, 25%

Summary and Discussion.—Spectrographic analyses of pyrite from Kerr Addison Gold Mine show the following:

1. Differences in grain size of pyrite appear to be related to some differences in minor element content, higher gold and silver occurring in very fine-grained compared with coarser crystals.

2. Compositional variations in pyrite from within quartz veins compared with that in adjacent wall rocks are for the most part slight with the exception particularly of titanium, which is best explained as due to inclusions left by replacement in wall rock pyrite.

3. Pyrite from different levels and localities in the mine, but showing similar geothermometer readings show very similar minor element content except in gold and silver. No outstanding differences in composition of pyrite appears related to different temperature readings.

4. Minor element content of pyrite in three different ore bodies is very similar in quantity, only one of the three appearing decidedly lower in Cr, Co, and Ti and higher in Mn than the others. Cobalt content varies from 0.033 to 0.04 percent and nickel from .04 to .05 percent.

5. Vertical variations in composition of pyrite down to the 2,500 level consist chiefly of an increase in gold and silver and a decrease in both cobalt and nickel. Other elements present in traces, such as Cr, Mn, Pb, Mo, Sn, and As show very slight and probably insignificant increases in the lower half of the mine.

These results suggest that the pyrite in the flow type ore of this deposit was deposited under rather similar conditions and from one ore-bearing fluid. The more marked variations in gold and silver in some cases may be best explained, as suggested by Smith, and as is evident in specimens with visible gold, by the later introduction of at least some of these metals into the pyrite after its original formation. This will also explain higher gold in the very fine type of pyrite into which late solutions could penetrate more readily than into larger crystals.

The results confirm statements made by the staff that conditions of ore deposition throughout the developed part of this deposit have been remarkably consistent and uniform except for an increase in amount of sulfides in the flow type ore with an increase in depth. Analyses suggest that at the same time gold-silver content of the pyrite is also increasing slightly and cobalt and nickel are decreasing with depth. Further sampling of the lower levels would probably be desirable before attaching too much importance to these indications.

PYRITE FROM KIRKLAND LAKE GOLD BELT, ONTARIO.

Introduction.

Samples of pyritic ore were obtained from seven producing mines of the Kirkland Lake gold belt through Dr. J. E. Thomson, Ontario Department of Mines. The area represented by these extends laterally for a distance of three miles and vertically to a depth of about 6,000 feet (Fig. 2).

The geology of this area and of the individual mines has recently been redescribed by Thomson (24) and the mine geologists. Details on the mineralogy of the ores by the present author, based on both hand specimen and polished section study of all samples subject to spectrographic analyses, are also contained in this report.

Briefly, the main ore zone of the Kirkland Lake camp extends in an easterly direction for about 3 miles and has a maximum width of 1¼ mile. It follows an important thrust fault system that transects a composite syenitic intrusive stock and dips steeply south. The deposits consist chiefly of fracture fillings and replacements along brecciated zones related to the faulting. Mineralization is characterized by the relative abundance of the tellurides of lead, mercury, gold, and silver as well as visible gold.

Though the most abundant sulfide in the ores, pyrite is present usually in amounts less than 2 percent. Practically all of it is in exceptionally fine grains, less than 0.5 mm and grading down to a micron or less in diameter. In only one case was coarser pyrite, 10 mm diameter from the Sylvanite mine studied. Almost all of the pyrite analysed came from mineralized wall rock, insufficient amounts from quartz veins and stringers being available for separate study.

Microscopic examination indicates that rarely is the pyrite pure. In the various wall rocks present, namely, syenite porphyry, syenite, augite syenite, tuffs, and sediments, pyrite is found replacing all primary minerals as well as secondary carbonates, but a distinct preference is shown for intergrowths of magnetite-ilmenite, augite, hornblende, or their carbonate-chlorite equivalents. In some cases remnants of graphically arranged ilmenite may be found in the

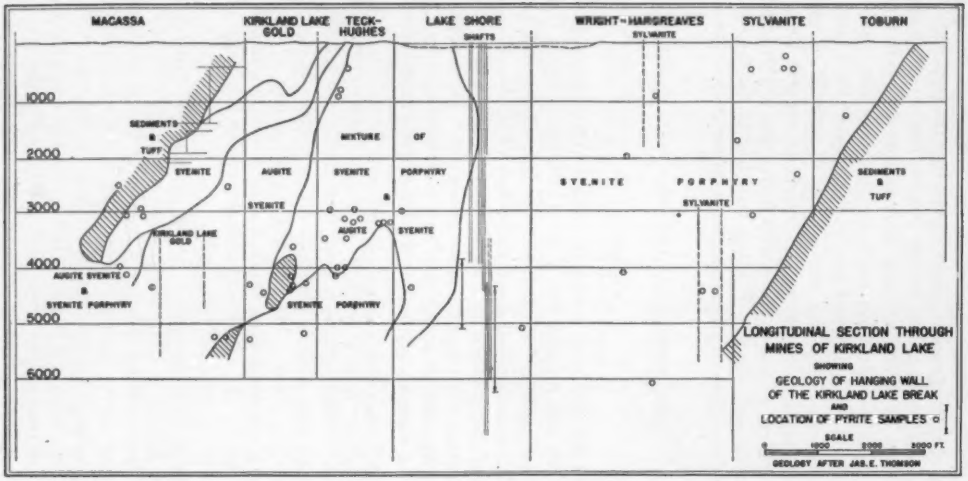

FIG. 2. Longitudinal section through mines of Kirkland Lake showing geology of hanging wall of Kirkland Lake fault (p. 33), and location of pyrite samples.

central core of pyrite, around which purer pyrite has been deposited. Other inclusions consist of exceptionally fine particles of gangue minerals, carbonates, gold, chalcopyrite, and various tellurides, chief of which are altaite, coloradoite, and calaverite. Accordingly it is recognized that analyses of pyrite obtained represent trace elements in both pyrite and inclusions, and though results in individual samples may show erratic distribution of certain elements, averaging many analyses is considered as satisfactory a method as is possible to determine general variations laterally and vertically.

Methods of spectrographic analysis are given under Introduction.

Qualitative Spectrographic Analyses.—Elements detected in Kirkland Lake pyrites by dc arc method include Na, Ca, Ba, Sr, Al, Si, Mg, Cu, Co, Ni, Cr, Mn, V, Mo, Ti, Te, Zn, Au, Ag, and Pb. Only the most sensitive lines of zinc and rarely those of tin and arsenic were observed in some samples and these elements as well as tungsten, antimony, and bismuth are on the whole absent.

Sodium, calcium, magnesium, aluminum, and likely barium and strontium are due probably to gangue inclusions, and titanium to remnants of unreplaced ilmenite. Gold, silver, and lead correspond generally in relative amounts to the tellurium present though in some cases the precious metals appear in excess. This reflects the presence of altaite with or without free gold. Only one sample out of 80 showed gold without detectible tellurium. About 25 percent of samples analyzed containing traces of gold show no titanium but the remainder show both elements, all of which suggest that gold is not limited to any particular generation or type of pyrite.

Cobalt and nickel are invariably present, with chromium and manganese almost always indicated but in very minor amounts. Vanadium is still less constant. Of these cobalt and nickel are likely in solid solution. Molybdenum may be present as minute particles of molybdenite, and copper is due undoubtedly to intergrown chalcopyrite.

Relative Intensity Ratios of Minor Elements.

Intensity ratios of 13 elements were determined by densitometric means using iron as an internal standard. Since samples of all but a special collection from one mine were excited in open crater electrodes the results of these are not directly comparable to those of other deposits described in this paper. None the less they show for this particular camp relative variations in composition of pyrite from place to place. Sixty-six samples were analyzed in this manner and fifteen of a special suite by the pellet method. For the latter, actual percentages of nickel and cobalt were also determined.

Variations in composition of the pyrite are reviewed according to (a) size of grain, (b) occurrence in different wall rocks, (c) in different mines and veins, and (d) with regard to depth.

Variations in Pyrite with Size of Grain.—Two examples were studied to determine differences in minor elements in pyrite which might be related to size of grain. Coarse pyrite cubes, about 10 mm diameter, from No. 5 Strike fault on the 4,800 and 5,400 levels of Sylvanite Mine were compared with the

average of 12 concentrates of finer-grained pyrite from this mine. Results show that the coarser pyrite, in this instance, is very much purer in all elements with the exception of titanium, than the finer-grained. This seems the one instance encountered where there are possibly two generations of pyrite, though as each type occurs separately there is no indication of their age relations.

On another specimen from the H vein of Teck Hughes mine, 28th level (3,351 feet), somewhat coarser than average pyrite (plus 1 mm dia) was compared with the finer pyrite associated with it. In this case, however, differences in minor elements are very slight and very similar ratios were obtained for Cr, Mn, Co, Mo, Ba, and Pb. Somewhat higher Ni and Ag appear in the coarser but it is concluded both types are more or less contemporaneous in origin.

TABLE VIII.

INTENSITY RATIOS OF ELEMENTS IN PYRITE IN DIFFERENT HOST ROCKS.

Element	Syenite porphyry	Syenite	Augite syenite	Tuff	Carb. schist
No. samples	14	3	3	4	1
Au	5.5	3.3	2.5	3.3	—
Ag	45.2	38.4	8.9	54.8	1.6
Te	2.1	1.5	1.6	1.7	2.1
Pb	9.1	8.2	12.4	5.6	6.7
Co	14.0	9.6	7.5	14.5	71.5
Ni	30.4	14.3	27.1	15.1	90.0
Cr	5.2	3.9	5.6	1.3	26.8
Mn	4.3	3.8	6.3	3.8	5.4
Mo	3.9	10.5	2.5	0.8	1.0
Ti	1.5	5.2	4.6	1.6	2.5
V	0.7	2.0	1.5	1.1	—
Ba	31.9	5.6	52.0	10.7	5.8
Sr	9.2	0.5	15.1	4.9	—

Variation in Intensity Ratios of Elements in Pyrite in Different Wall Rocks.—Distribution of samples in different wall rocks is shown for most cases in Figure 2. The greater number of samples are from syenite porphyry with smaller numbers from syenite, augite syenite, tuff, and schist. Results are given in Table VIII.

On the whole, differences are not extreme. In the case of the three intrusive rocks this probably reflects in part their close similarity in composition and genesis. Pyrite from the syenite porphyry and syenite is higher in Co, Ag, and Au than that from the augite syenite; that from syenite porphyry and augite syenite is higher in Ni, Cr, Ba, and Sr, while tellurium is highest in pyrite from the porphyry, lead from the augite syenite, and titanium from the syenite and augite syenite. Since some of the variation is due to inclusions, particularly in the case of titanium, no special significance can be attached to them.

Pyrite from tuffaceous rocks appears particularly high compared with others, in cobalt and silver, the latter in spite of the lowest gold and lead ratios.

Pyrite from carbonated schist in the north cross cut, Lake Shore, which is well away from the main ore zone, shows exceptionally high chromium, nickel and cobalt, low silver, and no detectable gold though lead and tellurium are present. The latter clearly indicate a genetic relation to the mineralization in the main ore zone.

Variations in Pyrite in Different Mines and Veins.—Comparison of the composition of pyrite in the different mines of the Kirkland Lake camp is afforded by Table IX which, at the same time, shows average variations to the east and west of the Lake Shore shafts.[4] To some extent these are affected by wall rock differences since more basic rocks are present to the west than to the east of the dividing line as shown by titanium, again.

TABLE IX.

COMPARISON OF PYRITE FROM EAST AND WEST OF LAKE SHORE SHAFTS KIRKLAND LAKE, ONTARIO.
(Relative intensity ratios—Fe as internal standard.)

Mine	No. samples	Au	Ag	Te	Pb	Co	Ni	Cr	Mn	Mo	Ti	V	Ba	Sr
East Section														
Lake Shore	1	5.3	60.0	1.4	4.2	14.7	7.6	9.5	4.0	2.6	0.5	2.8	—	6.0
Wright-Hargreaves	3	8.1	32.7	3.1	15.0	13.9	30.3	3.2	3.7	3.4	1.2	0.3	37.9	10.7
Sylvanite	12	5.0	40.8	3.0	9.6	13.3	31.6	5.1	3.9	4.3	1.7	0.6	32.2	4.3
Toburn	1	9.7	100.0	3.6	17.0	16.9	29.9	4.7	12.2	4.8	3.6	1.0	33.3	7.3
Average	17	5.9	43.9	2.2	10.7	13.7	29.7	5.0	4.4	4.1	1.6	0.7	31.4	8.9
West Section														
Lake Shore	2	4.4	59.4	2.9	15.5	14.3	32.9	3.3	7.7	1.5	4.5	—	44.0	22.5
Teck Hughes	17	1.7	34.2	1.3	8.0	14.3	27.2	6.1	4.7	2.8	3.5	1.8	13.1	6.1
Kirkland Lake	16	3.9	49.2	2.3	9.3	19.6	31.7	5.7	3.8	1.3	2.3	1.5	12.9	5.9
Macassa	9	4.4	35.1	2.5	13.0	10.1	23.4	7.4	4.4	5.4	5.1	2.7	13.2	0.6
Average	44	3.2	41.1	2.0	9.9	15.4	28.2	6.1	4.5	2.7	3.4	1.8	14.5	5.6

Most striking is the similarity in cobalt, nickel, silver, and tellurium in individual mines and in the chromium, manganese, and lead averages of east and west groups. The samples from the east are somewhat higher though not outstandingly so, in gold, molybdenum, barium, and strontium, and lower in vanadium and titanium, compared with those from the west, though it is admitted a larger number of samples from the east might even out some of these differences. Barium varies most and in the east is twice that in the west. Ratio of Co : Ni (intensity ratios) is about 1 : 2, similar to much of the pyrite showing low temperature readings in the Porcupine area.

Differences in pyrite from different veins are in part shown by the above results, but the greater similarities noted reflect, of course, the general similarity and continuity of mineralization along the "main break" of Kirkland Lake.

[4] This does not include the special suite from Lake Shore studied under different spectrographic conditions.

For a first hand description of these the reader is referred to Dr. Thomson's report and maps. Samples from Teck Hughes mine, in addition, show individual differences in cobalt and nickel in veins known as E, F, J, H, Q, and R, now available only at different levels. Pyrite in E, J, and H veins is notably high in silver, but sampling of these has been insufficient to allow other worthwhile comparisons. In individual cases, however, in this camp, while differences in minor element content may appear locally as noted elsewhere by Auger (3, p. 423) the overall averages are believed more reliable, and, as stated above, differences are of a rather minor character.

Variations in Pyrite with Depth.—Two studies of the variation in composition of pyrite with depth in the Kirkland Lake area have been made by slightly different spectrographic means. One of these consisted of a suite of pyrite specimens from the Lake Shore Mine covering the vertical interval from the 3,950 to 5,200 levels in a section 600 feet west of the main shaft, and from the 4,450 to 6,325 levels at the shaft section. The other study included specimens from all mines along the belt which have been examined individually and collectively.

TABLE X.

AVERAGE INTENSITY RATIOS OF TRACE ELEMENTS IN PYRITE, LAKE SHORE GOLD MINE.

Depths	Au	Pb	Co	Ni	Cr	Mo	Ti	V
3,950–4,950	19.9	22.1	9.7	5.5	17.2	31.8	9.2	6.4
4,950–5,700	31.7	29.3	7.3	6.6	10.5	29.7	8.1	6.2
5,700–6,325	13.3	15.3	11.2	6.8	19.8	27.3	12.5	4.6

Lake Shore Suites.—Pyrite from 15 samples was analyzed in triplicate using 10 mg samples with an equal weight of graphite compressed into pellets as described above. The excellent order of reproducibility of these with DC arc has been illustrated by Wark (25).

Averaging the intensity ratios for 8 elements (iron as internal standard) over three vertical intervals, gives the results in Table X.

With the discharge used, Mn varies from extreme over the 4,950 to 5,700 interval to trace above and below. Silver also shows too heavy lines for determination particularly in the deeper levels. Of the elements listed in Table X, gold and lead first increase and then decrease on the lower levels. Cobalt, chromium, and titanium decrease downward and then increase, while nickel increases slightly and vanadium decreases with depth.

Broader relations of trace elements in 57 samples of pyrite with depth are given in Table XI which shows average intensity ratios of 9 elements in pyrite from seven mines. In section A of this table arbitrary levels are chosen in 1,000 foot intervals. In B a slightly different grouping has been made though differences in results are slight. Detailed results for each mine are not given, but some of the more noteworthy variations are indicated.

From Table XI and results on individual mines not listed, gold and lead are slightly higher over the 1,000–3,500 interval and again on the lower levels.

TABLE XI.

AVERAGE INTENSITY RATIOS OF TRACE ELEMENTS IN PYRITE WITH DEPTH, KIRKLAND LAKE MINES.

Depth, feet	Samples	Au	Ag	Te	Pb	Co	Ni	Cr	Mn	Ti
					A					
0–1,000	10	3.5	39.6	1.2	7.8	11.2	23.9	6.7	4.6	3.7
1,000–3,000	5	5.1	57.7	3.6	11.7	12.5	30.1	2.9	4.0	2.1
3,000–4,000	19	3.6	36.5	2.1	11.2	10.4	28.6	5.7	4.8	2.8
4,000–5,000	17	3.3	41.6	1.9	9.0	15.8	32.9	5.4	3.6	3.0
5,000–6,150	6	4.6	33.9	1.8	13.3	18.3	29.5	8.4	6.3	2.4
					B					
0–1,000	10	3.5	39.6	1.2	7.8	11.2	23.9	6.7	4.6	3.7
1,000–3,500	19	4.7	45.4	2.7	13.1	10.6	29.6	5.4	5.1	2.5
3,500–5,000	22	3.2	36.3	1.8	6.9	16.3	31.5	5.1	3.4	2.7
5,000–6,150	6	4.6	33.9	1.8	13.3	18.3	29.5	8.4	6.3	2.4

Silver appears to decrease from the 3,500 level downward. Tellurium, like gold, is higher over the 1,000–3,500 interval but remains quite constant below. Cobalt on the whole increases slightly at depth, but at both east and west ends of the camp (Sylvanite and Macassa Mines) it remains quite constant. Actual percentage of cobalt varies from 0.029 to 0.101 percent in Lake Shore specimens. Nickel is, on the whole, fairly constant with depth though in five individual mines it shows a slight increase downward. Percentages of Ni determined in Lake Shore specimens vary from 0.060 to 0.10. Chromium varies as in the Lake Shore suite. Variations in manganese and titanium are slight and irregular.

Summary.

Qualitative spectrographic analyses of pyrite from the Kirkland Lake gold belt show the presence of twenty minor elements, many of which, such as Au, Ag, Te, Pb, Cu, Ti, Al, Mg, Cu, Ba, and Sr, may be related in part at least to minute inclusions. Little Sn, Zn, and As are present while Sb, Bi, and V are absent.

Quantitative analyses show cobalt present in amounts of 0.029 to 0.101 percent and nickel varies from 0.06 to 0.10 percent in Lake Shore samples. Average intensity ratios of Co and Ni are in the proportion of about 1 : 2, which, as shown later, is similar to that in some pyrite from the Porcupine area. Throughout the camp over a distance of about 3 miles and to a depth of over 6,000 feet, the pyrite is remarkably uniform in its fine size and in minor element content. By intensity-ratio studies of individual elements variations with size of grain, wall rocks, different mines and veins, and with depth, have been noted.

Rare, coarse pyrite, from one locality only, is sufficiently different from the usual fine-grained material to suggest a difference in age or origin. Wall rocks, though themselves not varying greatly, appear to have had only slight effects on

the pyrite, though some differences are noted. In the syenitic intrusives, pyrite in the syenite porphyry and syenite appear higher in Co, Ag, and Au. Pyrite from tuffs is peculiarly high in Co and Ag though Au and Pb ratios are low. Some variations are noted in different mines and veins but a striking similarity is shown in averages of both individual mines and in those lying east and west of the Lake Shore shafts in content of Co, Ni, Ag, Cr, Mn, and Pb.

Comparison of all samples with respect to a depth of over 6,000 feet show a remarkable uniformity and no extreme difference in any element. Cobalt remains quite constant at both east and west ends of the camp but on the average increases slightly downward. Though gold, tellurium, silver, and lead are highest in the 1,000–3,000 vertical interval, gold and lead are practically the same on the lowest levels, tellurium is constant from 3,500–6,150, while silver declines at depth.

There is clearly little to indicate any marked change in the general conditions of mineralization throughout this famous camp to a depth of over 6,000 feet. Whether the slight differences noted presage the beginning of changes at still greater depth can only be ascertained by future development. These are so small that rather may the general conclusion [5] be drawn that, provided favorable structural and general geologic conditions continue to still greater depths, no pronounced or sudden change in the character of the mineralization of this belt is to be expected for additional thousands of feet.

PYRITE FROM THE PORCUPINE GOLD DISTRICT, ONTARIO.

Introduction.

Through the kindness of one of the gold mining companies of the Porcupine District, Ontario and Dr. F. G. Smith, University of Toronto, an extensive suite of pyrite specimens were obtained for spectrographic study. These are from several different veins and wall rocks, from areas within intrusive porphyry masses or contiguous to them in schistose volcanics, and from depths varying from near surface to over 5,000 feet. All the samples of coarse-grained pyrite were studied by Smith (21) and temperature readings made by the pyrite geothermometer. The suite thus allows not only study of the relation of trace element composition of pyrite to depth of occurrence, but also to the temperature readings believed by Smith to represent temperature of formation or deposition of the pyrite.

The general geology of the area is ably described by Burrows (4), Hurst (15), Robinson (19), Langford (18), and more recently by Dunbar (9), Jones (16), Furse (10), and others. Quartz and quartz-carbonate veins follow single or multiple fracture zones in both altered and schistose volcanics, varying from dacites to basalts, and in quartz-porphyry bodies intrusive into the volcanics. Vein quartz in places contains fine to coarse pyrite, and native gold, but on the whole the veins are more sparingly mineralized with auriferous pyrite than the adjacent wall rocks alongside or between veins and stringers.

[5] It is of interest that, since this paper was written, deep drilling at Lake Shore has indicated a new high grade ore zone on the 7,825 foot level, thus confirming the above conclusion.

Sulfide type ore bodies are described by Furse (10) as consisting of pyritized and sericitized dacite in which cubes of auriferous pyrite $\frac{1}{16}$–$\frac{1}{4}$ inch in size are evenly disseminated. This type occurs where "quartz veins pass from sheared and fine-grained rock into unsheared coarse-grained rock."

The history of vein and ore formation is complex, but most authors believe that the mineralization took place over a considerable period of time during which intermittent fracturing and deformation occurred in such a manner that later minerals were introduced only in those places where suitable openings were available. Three phases of mineralization are noted, first, possibly ankerite followed by quartz-scheelite-tourmaline (Jones, 16) or barren quartz-tourmaline (Langford, 18), second, a main period of quartz-ankerite deposition with sulfides including arsenopyrite, auriferous pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, tellurides (petzite, tellurbismuth and minor coloradoite, J. E. H.), and gold, and finally a barren quartz-calcite stage.

Veins in the porphyry are considered by Allen and Folinsbee (2) as showing some zoning, the veins in the Pearl Lake mass containing scheelite, tourmaline, apatite, and albite-oligoclase, whereas those in the Millerton porphyry carry no tourmaline or apatite and somewhat less feldspar and ankerite.

Jones (16) states there is little evidence of vertical zoning over a depth of a mile, but mentions that on the lower levels gold is confined to quartz, and pyritized wall rocks are (relatively) barren.

A detailed study of the paragenesis of the Hollinger veins, which are very similar to those of the present investigation, has been given by Keys (17), who states that most of the pyrite associated with the veins occurs as imperfect cubes rarely over 3 mm in diameter, and where abundant, less than 0.3 mm. Most of the smaller cubes are rounded and contain irregular inclusions of quartz, carbonate, and sericite. . . . More pyrite is in the wall rocks than in the veins and much of the former, particularly along vein margins, is checked by minute fractures, some of which are filled with quartz or carbonate. Pyrite in the veins is described as "generally much coarser than the variety in the wall rock, with massive and imperfectly crystallized forms more common."

According to Keys and our own observations, gold occurs both in wall rocks and veins, much of it being concentrated along the margins. In the former, much of the gold is associated with pyrite which shows little if any difference from gold-free pyrite. Gold may be present as blebs on the surface of pyrite cubes or within them. It appears also in tiny fractures in the pyrite, though it is obvious polished section studies cannot prove that all the gold was so introduced or that some, in invisible particles, was not contemporaneous with the pyrite. Aside from what might be termed primary gold with the pyrite, no evidence has so far been produced that more than one period of later introduction occurred.

Smith's (21) temperature studies of pyrite and other minerals indicated to him at least two separate stages of mineralization, "the first extending over a range of 650° to 400° C at a depth of 10 kilometers and the second at 150° C at much shallower depth." He noted particularly that variations of temperature recorded bore no relation to depth or to individual veins, but were clearly

related to the distance of the pyrite from the contact of quartz porphyry masses with volcanics, and concluded that "the mineralization and porphyry intrusives are closely related in space, time of emplacement, and probably also in origin."

Spectrographic Methods.

Samples of pyrite were carefully selected from specimens available as in other studies, and spectrographic analyses made on two milligram samples compressed on flat-topped graphite pellets, as described above. Exposures of 10 seconds were made, the transmission being varied from 12 to 6 percent by use of filters depending on the density of lines of Au, Ag, Co, and Ni. Spectrum analysis film No. 2 was used entirely in this study and all procedures were carried out under uniform conditions. Intensity ratios of 14 elements were determined where possible, using suitable nearby iron lines as internal standards. Reproducibility tests of intensity ratios show that for elements present in more than only trace amounts, deviations from the mean average were somewhat less than 10 percent (cobalt and nickel actually gave approximately 4 percent deviation), though for elements present in amounts near the limit of detectibility this may be as much as 20 percent.

It is again noted that intensity ratios given in the following tables do not represent absolute amounts of elements. Ratios for any one element are to be compared only with others of the same element in different samples. Quantitative determinations for cobalt and nickel were made as outlined above.

Variables Studied.

Examination of specimens and of preliminary results indicated that in this study at least six different variables require consideration in assessing the significance of variations in trace elements in the pyrite.

These are:

a. *Size of grain*—Several different sizes of pyrite ranging in dimension from 10 mm to less than 0.2 mm in diameter may be present in close contact in single specimens of ore. In others the size may be fairly uniform. In general, where temperature readings by Smith are given, these apply to the coarser-grained pyrite present.

b. *Temperature readings* on pyrite by the pyrite geothermometer, as given by Smith, temperatures ranging from 125° C to 625° C. The pyrite falls into three classifications, those giving low temperature readings, those giving only high temperature readings, and some giving both low and high readings, denoted as two-temperature pyrite.

c. *Host rock*—such as quartz in veins, quartz-porphyry, black carbonaceous slate, sericite schist, or chlorite-sericite schist derived from volcanics.

d. *Distance from quartz porphyry contacts,* both within the porphyry, denoted in table by (+) sign, and away from it, denoted by a (−) sign.

e. *Vertical depth,* and

f. *Different veins,* of which 13 were examined spectrographically.

Variations in intensity ratios of the fourteen elements detected range from very marked and erratic, as in the case of Au, Ag, Co, Ni (Sn in some samples and veins) to moderate as in Pb, Ti, Mn, and Zn, to low for those elements present in lowest concentrations such as Mo, V, Sn, and rare Bi.

Variables Studied.

Variations in Composition of Pyrite with Size of Grain.—Although Keys (17) notes that individual crystals of pyrite increase in size in the wall rocks away from the veins, in some of our samples, pyrite of various sizes occurs within the veins and wall rocks and adjacent to them, and locally coarser pyrite may occur within the vein, and finer in the wall rock.

Spectrographic studies were made of three specimens, No. 217, 2,030 level, from the quartz of which *six* different samples of pyrite were obtained, No. 64, 800 level, yielding small cubes from quartz-carbonate vein and a mixture of small and coarse cubes from wall rock, and No. 272, 2,000 level, which gave three varieties of pyrite in quartz and only fine pyrite in adjacent schist. The results of analysis of these, expressed in intensity ratios, are given in Table XII and XIII. Pyrite in the first two specimens gave high temperature readings, while that from the third gave a low temperature reading of 175° + 75° C on the coarser material.

Physical differences apparent in the six samples Spec. 217 (Table XII) are as follows:

(1) Large cubes (L.C.) over 2 mm dia., fresh and compact.
(2) Large cubes (L.C. fract.), i.e., fractured and easily disintegrated or granular.
(3) Tarnished surface of large cubes (L.C. tarn.), deep yellow, but otherwise similar to No. 1.
(4) Small cubes (S.C.) 2–0.2 mm dia., compact.
(5) Small cubes (S.C.) probably fractured and healed with quartz which was not entirely removed.
(6) Fine pyrite—less than 0.2 mm dia., in more or less powdery form.

Similar designations are given to pyrite in specimens 64 and 272 (Table XIII).

Table XII gives the intensity ratios of 12 elements in Spec. 217 pyrite as shown by the six different samples, the "average" sample, and an arithmetic average of the six for comparison with the picked "average" sample. Strict comparison of the latter two, columns 7 and 8, should not be made, since relative amounts of the different types of pyrite were not determined. The large cubes (1) are the purest in content of the variable elements.

Only traces of gold appear in all but the average picked sample, which is richer, due likely to an erratic inclusion of gold. Silver, with the exception of the larger cubes, shows only a slight variation. Cobalt is decidedly lower in the coarse and higher in the fine pyrite, and nickel shows a similar but less marked variation in this direction. Manganese is strikingly higher in tarnished surfaces of large cubes and also in the fine pyrite. Other elements

present in low concentrations show correspondingly low variations, but titanium and arsenic are distinctly higher in the small cubes and fine pyrite than in the coarse-grained material. Chromium and bismuth were not detected. A further comparison of the effect of grain size along with differences in host rock (vein and wall rock) and in temperature readings as determined by Smith, is given in Table XIII for Specs. 64 and 272. Pyrite in the both vein and wall rock of Spec. 64, though in small cubes in the former and occurring as a mixture of small and coarse cubes in the schistose wall, gives almost identical intensity ratios for gold, cobalt, nickel, manganese, molybdenum, vanadium, and zinc. High tin in the wall rock pyrite is characteristic of certain veins (see below). Differences in silver and lead are not accounted for.

TABLE XII.

SHOWING VARIATIONS IN COMPOSITION WITH TYPE AND SIZE OF PYRITE.
(Intensity Ratios.)
Specimen 217, in Quartz, T—650°, Elev. 2030.

	1 Large cubes	2 L.C. (fract.)	3 L.C. tarn.	4 Small cubes	5 S.C. SiO_2	6 Fine pyrite	7 Aver. sample	Arith. average
Au	tr	tr	tr	tr	tr	tr	.574	
Ag	.85	3.10	2.63	1.70	2.67	2.67	2.09	2.27
Co	.12	.40	.36	1.20	1.20	1.30	.195	.76
Ni	.34	.30	.58	.60	1.5	.66	.53	.66
Mn	.25	.77	2.34	1.91	3.75	2.46	1.96	.91
Pb	.26	.66	.41	.49	.52	.74	.48	.58
Mo	.46	.43	.48	.44	.59	.61	.51	.50
V	.37	.38	.42	.42	.69	.55	.36	.47
Sn	.56	.48	.37	.66	.69	.64	.68	.57
Ti	.26	.57	.62	1.78	4.0	2.55	tr	1.62
Zn	.39	.50	—	.40	.53	.38	.52	.36
As	nil	—	—	.31	.34	.35	—	
%Wt. Co	.003	.014	.013	.043	.044	.047	.006	.024
%Wt. Ni	.010	.010	.018	.018	.050	.018	.016	.020

In Spec. 272, on which only one low temperature reading was determined, the coarser pyrite carries more gold, silver, and arsenic than the finer varieties. As in Spec. 64, the fine-grained pyrite samples from both quartz and wall rock appear very similar except in manganese and lead and it seems very probable both types were deposited contemporaneously.

Comparing the results from the three specimens, two of the three show higher Co, Ni, Sn, and As, and lower Pb in the finer-grained pyrite than in the coarse. In the third sample the relative amounts are either similar or ratios are reversed. It is difficult, therefore, to actually ascribe differences in composition to actual differences in grain size. Where large and small cubes show a similar composition it is concluded they were formed under similar conditions if not contemporaneously. Variations in composition may be in part fortuitous and depend on minute inclusions, varying conditions of deposition,

TABLE XIII.

VARIATIONS IN PYRITE OF DIFFERENT GRAIN SIZE AND IN DIFFERENT HOST ROCKS.
(Intensity Ratios.)

	Spec. 64—Vein No. A (800 L)		Spec. 272—Vein No. A (2,000 L)			
	Small cubes in quartz carb., 510° C	S.C. + coarse in gray sch., 510° C	Coarse in quartz, 175° ± 25°	Small cubes in quartz	Fine in quartz	Fine in schist
Au	.63	.63	.95	tr	.63	.72
Ag	2.24	.94	1.76	1.17	1.12	1.40
Co	.23	.22	—	.30	1.00	.92
Ni	.29	.29	.31	.74	.74	.73
Cr	tr	tr	tr	tr	.90	1.12
Mn	.53	.51	.32	.47	1.76	.57
Pb	.41	1.47	.38	.32	.23	.15
Mo	.65	.57	.45	.64	.37	.39
Sn	.76	7.30*	.70	.85	—	—
V	.46	.44	.37	.44	.33	.36
As	—	—	.98	.82	.20	.18
Zn	.37	.36	.66	.38	.29	.24

* Erratic high tin.

or to introductions in fractures and on outer surfaces as on tarnished pyrite. In any case, it is apparent that averaging analyses of many specimens of comparable material is required before significant trends can be expected.

Variations in Composition of Pyrite with Temperature Recordings.—A comparison of the minor constituents in pyrite giving readings at low, high, and two temperatures, as determined by Smith, is made in Table XIV, in which the averages of analyzed samples from only quartz or quartz-carbonate veins

TABLE XIV.

VARIATIONS IN COMPOSITION OF PYRITE WITH TEMPERATURE READINGS.
(Intensity Ratios.)

Element	Pyrite-high temp. readings (400-650° C)	Two-temp. pyrite (400-650°) and 150° C	Pyrite-low temp. readings (125-200°)
No. samples	49	12	27
Au	1.13	.75	3.1
Ag	2.25	1.57	5.3
Co	1.01	.87	.41
Ni	.81	.79	.59
Pb	.62	.46	.61
Sn	1.34*	1.52*	.68
As	.13	.25	.31
Zn	.49	.49	.72
Mn	.74	.94	.90
%Co	.045	.038	.013
%Ni	.036	.035	.023

* High value due to erratics in samples from two veins.

are presented. These represent pyrite from 12 different veins, the majority of which lie in schistose volcanics, but include some from veins in quartz porphyry and slaty rocks. Elevations range from 200 to 5,375 feet. The effects of different wall rocks, individual vein characteristics, and elevation are considered later.

The average intensity ratios given show that gold, silver, and arsenic vary inversely as the recorded temperature, higher ratios occurring in the "low" [6] pyrite. Both cobalt and nickel ratios are higher in the "high" than in the "low" pyrite. Cobalt, in actual percentage, is greater than nickel in the "high" type and less than nickel in the "low" pyrite. Average ratios of lead and zinc are slightly less in the "high" type compared with the low, whereas, tin is appreciably higher in the former as might be expected.

TABLE XV.

COMPARISON OF PYRITE GIVING HIGH AND LOW TEMPERATURE READINGS—DIFFERENT VEINS. (Intensity Ratios.)

	Vein No. A		Vein No. B		Vein No. C	
Temp.	High	Low	High	Low	High	Low
No. samples	9	5	7	4	14	4
Au	1.50	3.12	.72	3.58	1.40	1.30
Ag	1.95	2.56	.82	10.69	2.63	3.90
Co	.83	.31	1.22	.25	.98	.78
Ni	.70	.63	1.38	.36	.64	.34
Pb	.43	.48	1.16	.89	.53	.59
Sn	.67	.75	4.48	.69	.70	.69
As	.08	.39	.09	.29	.12	.21
Zn	.46	.53	.62	.33	.53	.32
%Wt. Co	.035	.008	.055	.006	.042	.033
%Wt. Ni	.031	.025	.064	.013	.026	.012

Analyses of the "two temperature" pyrite show that this is similar to the "high" type of pyrite in respect to Au, Ag, Co, Ni, Pb, and Zn. Content of arsenic is close to that of "low" pyrite and it may well be, as Smith suggested, that such pyrite was formed at elevated temperatures, fractured, and later affected by lower temperature solutions, or vapors (as of arsenic) though our averages do not indicate any enrichment of this type of pyrite in gold or silver.

Table XV gives the results of analyses of "high" and "low" type pyrite from different veins. Vein A samples are from similar host rocks, quartz in schists, from the same general distances outside porphyry intrusives, and from elevations of 400 to 2,875 feet. Samples from Vein B are chiefly from veins

[6] Temperature recordings on pyrite have been interpreted by Smith as indicating actual temperature of deposition of the pyrite. Since there may be some question as to the validity of this, the present author in endeavoring to present only factual data, and, to avoid ambiguity in this respect, as well as for the sake of brevity, is adopting the prefix "high" for pyrite giving high temperature readings (400–650° C) and "low" for pyrite giving low temperature readings (125–200° C).

within quartz porphyry and from elevations of 3,625 to 5,375. Vein C samples are from the 2,000–3,625 levels and are made up of equal numbers from outside and inside the porphyry. Thus, these samples introduce variables other than temperature readings on the pyrite, but none the less may be compared with results given above in order to see if similar compositional variations occur with temperature differences.

Except for the high values for tin in "high" pyrite, vein B, the results on high and low types of pyrite for both veins A and B are in fair accord with averages given for pyrite in Table XIV. Again, higher gold, silver, and arsenic, and somewhat lower cobalt and nickel characterize the "low" type pyrite compared with the "high" pyrite. Pyrite of veins A and C, however, shows somewhat higher gold and silver ratios in "high" pyrite than the average of other veins. Cobalt of "low" pyrite in vein C is also somewhat closer to that of "high" type pyrite, but some of the many other factors involved may explain this anomaly. Silver, in general, increases with gold content, but not always proportionally.

In summary, then, there appears to be, with the exception of pyrite from one vein, a distinct difference in trace element composition of pyrite giving high and low temperature readings as determined by Smith. Those showing high temperature readings, on the whole, are lower in content of gold, silver, and arsenic, and higher in cobalt and nickel than pyrite giving only low temperature readings. Average results show opposite relations in the relative amounts of cobalt and nickel in the two types, but as suggested later (p. 292) wall rocks may influence the cobalt content and ratio of percentage cobalt to nickel may not be so significant as far as temperature control is concerned.

With respect to gold in pyrite, however, as shown by samples from vein A and C, and others listed in Tables XX, XXI, *as high or higher gold ratios may occur in pyrite giving high temperature readings as in that giving low readings.* Of 49 samples of "high" pyrite, *not showing any low temperature readings,* 21 percent show such ratios in gold and silver averaging 3.24 and 4.9, respectively. Of these, 7 are from veins in the porphyry and 4 from outside. In all, Co and Ni ratios accord with "high" pyrite. If all "high" type pyrite was originally deposited with a small trace content of gold and silver, as seems indicated, the erratics must indicate later infiltration of gold into these specimens. If such was the case, temperature studies failed to indicate that the later gold-rich solutions were at a lower temperature than when the pyrite was first formed, insofar as they failed to produce an effect giving rise to low temperature readings, since none were recorded in these cases. It would seem then that either such late gold was introduced at high temperatures, soon after deposition of the "high" type pyrite, or if emplaced at lower temperatures the effect on the pyrite was such as not to be detectible. (No evidence has been found to support the idea of two periods of gold enrichment.)

Examination of 27 analyses of "low" type pyrite, shows that about 41 percent of these show low trace values in gold with an average intensity ratio of 0.69, the remainder giving variable but high ratios (Table XIX). Thus, it would appear probable that both types of pyrite contained a small amount of gold as originally deposited, but that later, granted only one period of intro-

duction of gold, somewhat more was deposited in the "low" type pyrite, on the average, than in the "high" type. As a corollary, it should be noted that in both this and other deposits, high-temperature recordings or high temperature formation of pyrite, by no means excludes the possibility of it containing appreciable quantities of gold.

Variation in Composition of Pyrite with Host Rock.—The major variation in host rock of the veins is between quartz porphyry and volcanic or slaty wall rocks. In addition, variation in the actual matrix of the pyrite, that is from quartz of the vein itself to altered and schistose wall rocks, needs consideration.

Study of the analyses of pyrite giving high temperature readings and occurring in, or adjacent to, veins in the quartz porphyry may be contrasted with that in veins in volcanic rocks away from the contact. Some 17 samples of the former and 32 of the latter were made. The results show that Au, Ag, Ni, and Pb are higher in pyrite within the porphyry and at the contact, Co, Cr, Ti, and Sn are higher in pyrite outside the porphyry (high Sn, however, is close to the contact zone), while Mo, V, Mn, and As are about the same in both, the latter two particularly on the upper levels. Analyses of two-temperature and the "low" type pyrite within and without the porphyry show a similar behavior with respect to Co and Pb, but the opposite relation with respect to Au and Ag. Of these results only the higher Cr and Ti outside the porphyry may be logically ascribed to the influence of the wall rock. Other differences may be due to other factors though somewhat similar differences occur in individual specimens containing both vein and wall rock as noted below.

Variations in minor elements in pyrite obtained from single specimens consisting of both quartz veins and adhering wall rocks, were determined in a few cases as illustrated in Table XVI. An example given consists of a sample from vein B in which temperature recordings, indicated by Smith, are relatively high, and a sample from vein A in which pyrites in both vein and wall rock were of the "low" type. In both cases, pyrite in the quartz was relatively coarse-grained but in the wall rock (slate or sericite schist) was finer. This difference was unavoidable. As noted in the table the two samples are from different elevations in the mine.

In summary, gold is present in small but constant amounts in both quartz and slate, vein B, and in sericite schist of vein A, while silver shows slight variations. Both gold and silver are distinctly higher in pyrite in quartz of vein A. "High" type pyrite, vein B, *in the wall rocks* contains more Co, Cr, Mn, Ti, and Zn than pyrite in quartz whereas the pyrite *in quartz* is higher in Ni, and Pb. In the "low" pyrite of vein A again Co, Cr, Mn, and Ti are higher in pyrite of the wall rock whereas pyrite in quartz is higher in As as well as in Au and Ag. These variations are not altogether in agreement with those noted for coarse and fine pyrite in the same matrix, and may well be attributed in part to the influence of wall rocks. Attention has already been called to the similarity in composition of fine pyrite in both quartz and schist of Spec. 272, vein A, p. 289, 200 ft from the porphyry. As might be expected, the composition of pyrite does appear to be affected by the composition of the host rock and matrix in which it is emplaced, though one exception has been noted. The final re-

sult will depend on its manner of deposition and the extent of replacement of other minerals, if any.

Variations in Composition of Pyrite with Distance from Quartz Porphyry Contacts.—Examination of analyses of comparable pyrite of both "high" and "low" types occurring in veins or massive seams, shows that certain variations in gold and silver appear related to proximity to intrusive quartz porphyry bodies, as shown in Table XVII. In this table seven examples are given of both "low" and "high" types of pyrite, from various levels, and from areas both outside and inside the porphyry masses.

With the one exception of vein C, 2,125 level, all show higher gold and silver ratios closer to the porphyry contact than farther away. Though not listed, arsenic and zinc in most cases are slightly higher away from the contact than closer to it, but no particular trend is discernible in other minor constituents.

TABLE XVI.

PYRITE FROM SAME SPECIMEN—DIFFERENT HOST.
(Intensity Ratios.)

	Spec. No. 416, Vein B, El. 4,775′		Spec. No. 195, Vein A, El. 600′	
	In quartz, 475°, coarse	Slate, 510°, small cubes	In quartz, 170° C, coarse	Sericite, 170° C, fine
Au	.59	.62	2.37	.63
Ag	.77	.55	3.30	1.16
Co	.21	1.19	.16	1.0
Ni	1.60	.58	.27	1.0
Cr	tr	1.96	1.35	1.42
Mn	.40	.76	.43	.64
Pb	1.39	.27	.55	.55
Mo	.46	.54	.53	.47
V	.39	.45	.39	.41
Sn	7.0	10.0	.85	.72
Ti	—	.43	—	.32
Zn	.36	1.06	.73	.44
As	—	—	.21	.14

Since the examples given include material from three different veins and from various levels, some relation between gold content in both "high" and "low" types of pyrite and the porphyry contact zone is apparent. That such a relation is probably structural rather than thermal is evident by the fact that it holds in both types of pyrite, and hence cannot be attributed to such variations in temperature of "high temperature" pyrite, as shown by Smith (21, p. 631) to characterize the areas within or without the contact where he notes a "small amount of temperature zoning." Rather the results indicate, as suggested in the consideration of the relation between gold and temperature readings (p. 291), that this particular contact zone was a main channel way for post-pyrite, gold-rich solutions which became inpoverished as they travelled laterally on either side.

As illustrated in Tables XX and XXI, and also noted previously (p. 292)

TABLE XVII.

VARIATIONS IN GOLD AND SILVER IN PYRITE WITH DISTANCE FROM PORPHYRY CONTACTS.
(Intensity Ratios.)

Vein and level	No.	Temp.	Distance	Au	Ag
A-1,750	320	160°	−50′	8.27	5.5
-2,000	272	175°±25°	−200′	0.95	1.76
A-2,000	304	520°±100°	−130′	1.35	3.6
-2,250	425	450°	−310′	0.61	0.77
C-2,125	220	490°	−150′	0.76	3.12
-2,125	98	490°	−200′	1.90	5.00
B-3,750	478	460°	0	0.55	0.64
-3,750	479	475°±50°	−40′	0.47	0.64
C-2,125	180	620°	+200	4.45	5.9
	317	620°	+350	2.97	4.5
B-5,375	454	150° C	+140	0.61	2.0
	458	125° C	+220	0.49	0.38
C-2,000	129	500° var.	+270	4.82	5.0
	119	600°±50° var.	+400	0.61	0.43

(−) indicates distance away from porphyry contact.
(+) indicates distance within porphyry from contact.

cobalt is higher in pyrite occurring outside the porphyry, and nickel is higher in pyrite within the porphyry.

Variations in Composition of Pyrite with Depth.—In order to ascertain variations in composition of pyrite with depth, analyses of pyrite giving different temperature recordings have been averaged in Table XVIII for the up-

TABLE XVIII.

AVERAGE VARIATIONS IN PYRITE WITH DEPTH.
(Intensity Ratios.)

Element	Low type pyrite		High type pyrite		Two temp. pyrite*	
Levels	200–2,875′	3,000–5,375′	800–2,875′	3,000–5,375′	1,000–2,000′	3,125–5,375′
No. samples	16	11	25	23	4	7
Au	3.91	2.86	1.53	.71	1.09	.64
Ag	4.22	7.59	2.72	1.88	1.54	1.69
Co	.41	.46	.74	1.21	.75	.80
Ni	.74	.44	.64	.91	.40	.90
Pb	.56	.75	.40	.68	.39	.48
Sn	.69	.67	.67	1.32	.96	.65
As	.35	.27	.13	.07	.24	.29
Zn	.56	.39	.50	.40	.41	.62
% Co	.013	.015	.031	.055	.031	.034
% Ni	.032	.016	.026	.040	.014	.040

* Two-temperature pyrite samples come chiefly from 2,000–3,500 levels.

per levels extending down to 2,875 feet and for the lower levels from the 3,000 to 5,375 level. In addition, analyses of all "low" type of pyrite are presented in Table XIX, all "high" pyrite occurring outside porphyry bodies, in Table XX, and "high" pyrite from within the porphyry in Table XXI.

In all types of pyrite showing low, high, and two-temperature recordings, Table XVIII, gold is more abundant in the upper than lower levels. Highest

TABLE XIX.

VARIATIONS IN LOW TYPE PYRITE WITH DEPTH.
Intensity Ratios.)

Spec. No.	Temp.	Elev.	Dist. porph.	Au	Ag	Co	Ni	Pb	Sn	As	Zn
251 Q*	125°	200′	−60	.70	1.13	.15	.24	.25	.70	.28	.31
154 Q	175	500	−100	11.00	7.0	.21	1.98	.43	.63	.40	.79
195 Q	170	600	−65	2.37	3.30	.16	.27	.55	.85	.21	.73
195 S	170	600	−65	0.63	1.16	1.00	1.0	.55	.72	.14	.44
230 Q	150	800	cont.	.71	3.65	.10	1.37	1.02	.64	.27	.62
230 S	150	800	cont.	6.40	3.50	.71	.85	.99	.66	.29	>3.5
109 S	200	1,000	−75	.64	.66	1.16	.60	.22	.64	.42	.47
255 Q	125	1,000	−65	6.90	8.58	.32	.26	.27	.65	.25	.34
149 Q	155	1,500	−75	3.36	1.06	.10	1.20	.43	.72	.45	.34
320 Q	160	1,750	−50	8.25	5.50	.26	.36	.49	.77	.20	.48
272 Q	175	2,000	−200	.95	1.76	tr	.31	.38	.70	.98	.66
132 Q	160	2,100	−100	.53	.63	.14	.46	.21	.63	.32	.25
468 S	150	2,375	−250	2.60	7.00	.23	.71	.34	.72	.61	.90
432 Q	175	2,500	−30	.62	.62	1.15	.31	.21	.66	.21	.36
477 Q	150	2,500	+10	2.64	5.70	.18	.33	.59	.74	.29	.27
181 Q.S.	175	2,875		4.21	6.13	.27	.89	1.97	.63	.20	>5.0
398 Q	150	3,000	−70	.70	7.90	.28	.41	1.30	.69	.14	.34
406 Q	125	3,000	−20	1.26	2.16	1.48	.39	.25	.66	.23	.30
65 Carb.	150	3,125	−10	3.43	3.80 (23.0)	.86	.27	.27	.67	.24	.46
89 Q	1–200	3,500	cont.	6.12	>8.00 (23.0)	.12	.29	1.72	.69	.24	.40
295 Q	140	3,625	+50	7.40	>8.00	.28	.55	1.07	.68	.43	.40
116 Carb.	150	3,625	−90	1.05	1.77 (22.0)	.74	1.13	.18	.61	.26	.88
312 Q	150	3,750	−20	6.50	>8.0	.25	.52	1.40	.67	.41	.33
478 Q.S.	125	3,750	cont.	2.90	3.14	.30	.25	.46	.62	.48	.20
365 Q	150	4,325	cont.	1.01	.70	.11	.23	.50	.73	—	.34
458 Q	125	5,375	+220	.49	.38	.12	.45	.61	.74	.48	.24
454 Q.P.	125	5,375	+140	.61	2.00	.54	.27	.46	.67	—	.43
Average of 27 samples				3.09	5.29	.41	.59	.62	.68	.31	.72

* Q—in quartz; S—in schist of border; Q.P.—in porphyry.
Average—% Cobalt, .013; % Nickel, 0.023.

values of gold in pyrite in all samples appear more consistently from the 1,500 to the 3,750 levels than above or below, whether veins are within or without the porphyry. Attention may again be called to the rather remarkable uniformity of gold intensity ratios (about .60) in the "high" type of pyrite, excluding erratic high ratios, from top to bottom of the deposit. Actual amount of such gold is close to the limit of detectability (± .001 percent) (Ahrens 1950, p. 197) and it may be that the lack of truly barren pyrite should be stressed rather than

the uniform ratio. Silver shows opposite relations in the "high" pyrite compared with the "low" and two-temperature pyrite, increasing on the lower levels in the latter two types. Cobalt and lead increase slightly with depth in *all* samples no matter in which host rock. Nickel like silver shows opposite trends in "high" and "low" pyrite increasing at depth in the "high" type but decreasing in the "low." Tin, arsenic, and zinc are variable.

TABLE XX.

VARIATIONS IN COMPOSITION OF PYRITE WITH DEPTH.
HIGH TEMPERATURE TYPE FROM OUTSIDE PORPHYRY.
(Intensity Ratios.)

Spec. No.	Temp.	Depth	Dist. porph.	Au	Ag	Co	Ni	Pb	Sn	As	Zn	Cr	Mn	Mo	V	Ti	Bi
93	4–500°	400	− 70′	.60	1.14	.33	.76	.40	.67	.21	.33	.92	.52	.50	.42	—	—
64Q	510	800	−25	.63	2.24	.23	.26	.41	.76	—	.37	tr	.53	.65	.46	—	—
64S	510	800	−25	.63	.94	.22	.29	1.47	7.3	.39	.36	tr	.51	.57	.44	—	—
161	420	800	−200	.70	2.84	1.02	.78	.42	.60	.39	.35	1.32	1.20	.38	.42	.35	—
157	475	800	−150	.63	4.48	1.30	.54	.37	.65	.17	.30	1.18	1.14	.47	.40	.30	—
183	500	800	−75	.66	2.49	.66	.48	.38	.66	.23	.33	1.01	1.11	.62	.47	.33	—
155	500	1,250	−15	.62	.39	.45	.35	.27	.66	—	.28	.83	1.05	.50	.38	—	—
139	500	1,375	−90	.87	1.12	1.01	.79	.37	.66	.22	.71	tr	.70	.58	.33	.70	—
143	450	1,500	−130	6.40	5.00	1.40	.43	.57	.62	—	.38	1.05	.38	.47	.37	—	—
182	510	1,500	−30	.57	2.64	3.0	.66	.33	.62	—	.34	.94	.73	.44	.37	.20	—
145	630	1,500	−50	.71	1.41	.21	.86	.54	.68	—	.19	.75	1.36	.44	.32	—	—
99	460	1,750	−90	1.65	1.69	.84	.54	.78	.59	.17	.40	.75	.33	.44	.35	.33	—
217	650	2,000	−250	.57	2.09	.20	.53	.49	.68	—	.52	—	1.96	.51	.57	tr	—
98	490	2,125	−200	1.90	>5.0	.15	.33	.65	.83	.25	.53	.84	.67	.57	.38	—	.91
220	490	2,125	−150	.76	3.12	1.1	.94	1.34	.79	.28	2.46	.92	.24	.50	.39	.18	.96
375	500 v.	2,500	−10	.69	2.65	1.07	.82	.81	.71	.22	1.08	1.48	1.02	.63	.56	1.36	.38
327	var.	2,732	—	.60	1.72	.62	1.50	.39	.66	.71	1.04	1.17	1.37	.63	.54	.69	—
382	610	2,750	−80	.60	.62	.58	.36	.24	.62	.19	.37	.74	.27	.48	.38	.38	—
482	500 v.	2,875	−160	.87	.80	1.0	.40	.39	.59	—	.54	1.14	.74	.40	.31	.20	—
434	520	2,875	−55	1.16	2.00	.53	.27	.46	.67	—	.43	1.40	.35	.46	.50	.69	—
158	500	3,125	−110	.60	1.72	2.60	.72	.47	.66	.18	.58	.92	1.02	.46	.38	.18	.28
45	600	3,125	−60	.63	5.0	.58	.37	.28	.59	—	.33	1.11	.36	.53	.35	—	.35
441	500	3,250	−119	.68	1.28	.71	.73	.45	.65	.24	.37	.85	.45	.55	.46	—	—
59	480	3,250	−140	.65	3.90	4.0	1.43	.70	.71	.25	.46	.87	.70	.43	.41	.43	.52
224	500	3,500	−30	.60	.66	.56	.87	.82	.63	—	.27	.61	.29	.47	.38	—	—
479	475	3,750	−40	.47	.64	1.0	1.0	.74	.74	.18	.40	3.60	.57	.40	.34	.43	—
152	450	4,025	−15	.66	1.25	3.0+	.59	2.12	>6.0	.29	.35	tr	.35	.50	.39	—	—
416Q	475	4,775	−30	.59	.77	.21	1.60	1.39	>7.0	—	.30	tr	.40	.46	.39	—	—
416S	510	4,775	−30	.62	.55	1.19	.58	.27	10.0	—	1.06	1.96	.79	.54	.45	.43	—
502	500	4,925	−25	.60	.34	.50	.33	.22	.68	—	.31	.97	.29	.47	.36	—	—
496	500	5,225	−10	.63	1.10	1.0	.45	.17	.62	—	.23	.92	.39	.37	.32	.16	tr
506	500	5,375	−45	.61	.67	>3.0	.88	.36	.68	.54	.25	1.05	.47	.45	.36	.35	—
Average—400′–2,875′				1.1	2.22	.80	.59	.53	.97	.15	.56	0.78	.81	.51	.42	.28	.12
Average—3,125′–5,375′				.61	1.24	1.53	.79	.66	2.41	.14	.41	1.28	.51	.47	.38	.17	.09

>—greater sign; Q—in quartz; S—in slate or schist; var.—variable; −70′—away from contact prophyry.

Other elements such as Cr, Mn, Mo, V, and Ti, determined for "high" type pyrite, though not recorded here, are quite constant within the porphyry, though outside in volcanics slightly more Mn, Mo, V, and Ti appear in the upper levels and more Cr at depth.

Altogether then there appears to be a perhaps insignificant decrease in gold and silver with depth and an increase in cobalt, lead, and in some cases of nickel. None of the trends is at all outstanding.

Variations in Composition of Pyrite in Different Veins.—In order to determine if any of thirteen different veins examined showed any striking differ-

ences from others, the average trace element analyses stated in terms of intensity ratios of pyrite, giving both low and high temperature readings, were examined. Since some of the veins transect different rock types both laterally and vertically, and extend over different vertical intervals, differences in composition attributable to these factors are to be expected. If, however, all veins had essentially the same history no great differences would be expected.

Results of such comparisons have already been given (p. 290), in considering variations in pyrite with temperature in three different veins (Table XV). Of all 13 veins studied the only outstanding difference, as noted, is the occurrence of erratic high tin ratios in "high" type pyrite in two. In most cases these are from samples in or close to the quartz porphyry, and it seems possible they may be related to early high temperature mineralization indicated by

TABLE XXI.

VARIATIONS IN COMPOSITION OF PYRITE WITH DEPTH.
HIGH TEMPERATURE TYPE AT CONTACT OR WITHIN PORPHYRY.
(Intensity Ratios.)

Spec. No.	Temp.	Depth	Dist. porph.	Au	Ag	Co	Ni	Pb	Sn	As	Zn	Cr	Mn	Mo	V	Ti	Bi
270	5–600°	1000′	+25′	3.2	>4.0	.42	.84	.62	.59	.39	.41	1.2	.66	.45	.39	.46	—
175	600	1,265	cont.	.63	.63	.28	.55	.93	.76	.30	.40	—	.75	.68	.50	—	1.50
173	590	1,625	+90	.58	4.5	.11	.35	.27	.60	.18	.32	.79	.24	.46	.29	—	—
314	500	1,875	cont.	.60	1.0	2.5	2.38	.68	.71	.12	.77	1.0	1.35	.44	.35	.71	—
129	550	2,000	+27	4.82	5.0	.13	.41	.28	.60	.14	.26	.52	.23	.40	.28	—	—
119	600	2,000	+400	.61	.43	.30	.67	.39	.68	—	.23	.78	.24	.51	.40	—	—
180	620	2,125	+200	4.45	5.90	—	.22	.35	.75	—	.55	tr	1.22	.62	.39	—	—
317	620	2,125	+350	2.97	4.50	.22	1.05	.66	.77	.18	.27	.94	.66	.50	.36	—	—
400	490	3,000	cont.	.60	2.16	.21	.67	.55	.71	—	.50	.77	.39	.50	.39	—	—
401	475	3,000	cont.	.57	.46	1.17	.24	.23	.60	—	.23	.65	.48	.46	.34	—	—
72	480	3,125	cont.	2.60	9.0	2.33	.45	.57	.64	—	.42	.78	.99	.58	.43	.25	.53
223	510	3,500	+70	.55	1.31	1.30	3.0	1.83	.65	—	.58	.87	.39	.41	.34	—	—
403	500	3,625	+150	.60	2.0	2.0	1.0	.75	.84	—	.25	.80	.96	.47	.38	—	—
478S	460	3,750	cont.	.55	.64	.85	1.25	1.08	.78	.18	.52	1.23	1.07	.43	.38	.20	—
370S	600	4,475	+150	.53	1.06	1.66	2.65	1.51	6.00	—	1.34	tr	1.75	.50	.42	—	—
449	500	5,225	+275	.58	1.6	2.0	.69	.25	.63	—	.26	.63	.32	.41	.31	—	—
457	500	5,375	+230	1.64	6.0	.62	2.0	1.00	.84	—	.28	1.12	1.05	.41	.34	—	—
Average—1,000′–2,125′				2.23	3.25	.44	.81	.52	.67	.16	.40	.65	.79	.51	.42	.15	—
Average—3,000′–5,375′				.91	2.63	1.26	1.33	.87	1.3	.02	.49	.76	.82	.46	.37	.05	.06

tourmaline, or scheelite, or both. Tungsten apparently was not in sufficient concentration in any of our samples for detection. It is spectrographically insensitive, the limits of detection being between 0.1 and 0.01 percent.

Other differences in pyrite from various veins are of such an order that they may be explained by other factors already discussed.

Summary.

Six variables have been studied in considering the significance of spectrographic analyses of pyrite from a gold deposit in the Porcupine district, Ontario. These are summarized with results.

1. Variation in grain size of pyrite in single specimens show considerable variation in minor element content, cobalt and nickel being lower in the coarse and higher in finer sizes, while the reverse is true for titanium and arsenic.

Comparison of analyses of coarse and fine pyrite in a quartz matrix and in adjacent wall rock, and, in some cases, the marked similarity in composition of pyrite in vein and wall rock is such as to suggest contemporaneity of origin. In others, differences in composition of different sized grains may depend on many factors involved in their deposition.

2. Variations in composition studied in relation to temperature recordings made by F. G. Smith, by electrical and decrepitation methods, indicate that in general pyrite giving only high temperature recordings contains less gold, silver, arsenic, lead, and zinc but more cobalt, nickel and, in some veins, tin than that giving only low temperature readings. Pyrite giving both high and low readings from the same specimen has the characteristics chiefly of "high" pyrite except for arsenic, suggesting the latter may have been introduced at the lower temperature. Distribution of gold in all three types of pyrite is such as to indicate that only trace amounts were deposited originally and contemporaneously with the pyrite, and that larger quantities were introduced later into both "high" and "low" types of pyrite, more finding its way into pyrite of the "low" rather than the "high" type. Some twenty percent of the "high" pyrite samples show erratic high values in gold, but if this was introduced at lower temperatures, no low temperature effects were noted in temperature measurements. Pyrite showing both *low* as well as *high* readings shows no pronounced enrichment in gold, but, since the pyrite giving only low readings is on the whole richer in gold, though some 40 percent shows only trace values, presumably this gold was deposited at low temperatures. In any case the "low" type pyrite appears to have been a somewhat better precipitant for gold, due possibly to its less uniform atomic structure, but the "high" type pyrite, in places has been equally effective, hence original temperature of deposition of pyrite may only indirectly affect later gold deposition. Highest gold values in pyrite are from 1,500 to 3,750 elevations.

3. Composition of pyrite in veins occurring in quartz-porphyry are compared with those in volcanics and slates. Pyrite giving high temperature readings in porphyry is in general richer in gold, silver, nickel, and lead, while cobalt, chromium and titanium are higher in the surrounding volcanic assemblage. Molybdenum, vanadium, manganese, and arsenic are about the same in both. Comparison is also made of pyrite of different types from veins outside the porphyry in both quartz and slate or schistose matrices. That in the latter is for the most part also higher in cobalt, chromium, manganese, and titanium.

4. A rather distinct relation appears to exist between relative amounts of gold and silver in pyrite of both types and proximity to the contact of quartz-porphyry and volcanics. The relation is considered a structural one, favoring greater introduction of these metals along the contact zone.

5. No outstanding trend is apparent in trace element content of pyrite of different types to depths of over 5,000 feet though a very minor decrease in gold and silver and an increase in cobalt, nickel, and lead with depth is noted.

6. In 13 veins examined, the only notable difference is the occurrence in some of erratic high tin values which may be related to early high temperature mineralization indicated, in places, particularly by tourmaline and scheelite.

COMPARISON OF PYRITE IN DIFFERENT GOLD DEPOSITS.

Though an exhaustive qualitative study of the trace elements in pyrite of four different Canadian gold deposits was not made, minor constituents present in all include Au, Ag, Co, Ni, Cu, Cr, Mn, Mo, V, Pb, and Ti. Of these Mn, V, and Pb, and in some cases Cr are present only in trace amounts. Tellurium is present in all Kirkland Lake samples in sufficient amounts to study its variation, but was more rarely detected in samples of pyrite from the Powell Rouyn mine and in samples from the Porcupine area. Arsenic, tin, and zinc are present in all samples excepting those from the Kirkland Lake belt where all three are very rare. Bismuth is most prominent in the Powell Rouyn pyrite, is rare in Porcupine pyrite, and is not detectable in the others.

These results differ somewhat from those of Auger (3) who did not detect tin in Hollinger pyrite (Porcupine area) but did report cadmium, columbium, and yttrium, none of which showed in our samples.

TABLE XXII.

COBALT-NICKEL CONTENT OF PYRITE.

	Percentage	
	Cobalt	Nickel
Powell Rouyn, Que.		
Average 200–2,450 levels	.021	.043
Kerr Addison, Ont.		
Ore body 21—to 2,500 level	.040	.049
Ore body 16	.039	.050
Ore body 17	.033	.040
Kirkland Lake		
Lake Shore Mine	.029–0.101	.060–0.10
Average 3,950–6,325 levels	.045	0.78
Porcupine Gold District (one mine)		
Pyrite with high temp. readings	.045	.036
Pyrite with low temp. readings	.013	.023
Pyrite with two temp. readings	.038	.035

Quantitative determinations of cobalt and nickel in pyrite of the four deposits studied are given in Table XXII. In all except pyrite giving high temperature readings from the Porcupine area, cobalt on the average is present in smaller amounts than nickel,[7] but in the latter the reverse is true. The amounts of both nickel and cobalt in pyrite giving low temperature readings, Porcupine area, is decidedly less than in all the other pyrite examined, while that from the Kirkland Lake belt gives the highest nickel. Co : Ni ratio of pyrite from Powel-Rouyn, Lake Shore, and "low" type pyrite from Porcupine is about 1 : 2.

Insofar as the pyrite of the different deposits varies physically, as in size of grain (exceptionally fine in the Kirkland Lake camp), and also with respect

[7] This is the opposite of results given by Carstens as reported by Rankama and Sahama (Geochemistry, 1950, p. 674) for pyrite in hydrothermal veins in which no distinction is made between pyrite of high and low temperature origin. Our results for pyrite from Porcupine giving high temperature readings, are the only ones to agree with those of Carstens.

to its enclosing matrix, strict comparisons of minor element content cannot logically be made. The relative absence of tin, arsenic, and zinc in the Kirkland Lake pyrite, however, does appear in keeping with the general opinion that these deposits are more of mesothermal than hypothermal origin. Whether the relatively high nickel content of this pyrite is in keeping with this, is not known, but in any case it is a characteristic of this camp. On the other hand, the presence particularly of tin, in the other deposits lends weight to their usual classification as hypothermal, at least with respect to the early stages of mineralization. Arsenic, when combined with iron and sulphur as in arsenopyrite, may likewise be considered as indicative of higher hypothermal temperatures of formation (as in the Upper Canada gold deposits to the immediate east of Kirkland Lake), but it is of interest to note that in the Porcupine deposit studied, more of this element is associated with pyrite giving only low temperature recordings than with that giving high readings, and, accordingly, it is suggested much of the arsenic was deposited late in the sequence and presumably at relatively low rather than high temperatures.

VARIATIONS IN TRACE ELEMENT COMPOSITION OF PYRITE OF DIFFERENT DEPOSITS WITH DEPTH.

Though spectrographic procedures were varied somewhat in determining intensity ratios of minor constituents, samples of each suite were subject to identical methods, and, while it has been shown that other factors such as host rock or matrix, grain size, and vein type, as well as temperature effects as determined by Smith, may affect trace element composition of pyrite, overall variations in each deposit with depth may be compared.

In none of the deposits is there any outstanding change in composition of pyrite with depth. In fact the relative uniformity of the pyrite to depths from 5,000 to 6,000 feet should be stressed rather than any minor differences.

In the two deposits, Powell-Rouyn and Kerr Addison, sampled only to about 2,500 feet deep, such differences in composition as have been brought out are opposite in character. Thus, gold and silver decrease slightly in the former with depth, but increase more decidedly in the latter. Cobalt and nickel show slight increases in the one and decreases in the other, and opposite trends, though very slight, are noted for such elements as Cr, Mn, Pb, and Mo. Tin and vanadium show no change in the former nor zinc in the latter.

In the deposits at Kirkland Lake and the Porcupine, extending to depths of over 5,000 feet, the one common variation in pyrite is a slight increase downward of cobalt, though at the east and west ends of the Kirkland Lake belt cobalt is fairly constant. Certain vertical horizons (1,000–3,750) in both camps show highest ratios of one or more of gold, silver, lead, and tellurium, and, though gold shows a slight decrease in the lower levels of some mines, sampling at these horizons is possibly not sufficient to attach much importance to this.

Comparison of the present results on pyrite from the Porcupine area with previous determinations in Hollinger pyrite by Auger (3) shows some similarities and differences, the latter in part due to the fact that in the present

study, because of Smith's temperature determinations, differentiation has been made possible between types of pyrite. Auger has indicated that silver in Hollinger pyrite is uniform from surface to 2,400 feet but thereafter decreases. This is true of pyrite showing high temperature readings, but pyrite giving low temperature and two-temperature readings shows a slight increase in silver with depth. Cobalt increases at depth according to both investigations, and results on lead also indicate a final increase at depth after various fluctuations. Nickel, according to our results, increases in depth in the "high" type pyrite but decreases in the "low" type, where at Hollinger, Auger found a decrease only. No uniform decrease in zinc was noted by us as is indicated by Auger, and where he found a decrease in chromium our results show this remains constant in quartz-porphyry but increases at depth in the volcanics. Such divergencies may in large part be due to differences in original samples and emphasize a lack of, rather than any very definite trend with, depth.

SUMMARY AND CONCLUSIONS.

Spectrographic analyses by dc arc methods have been made on some 200 samples of pyrite from four Canadian gold deposits in order to study variations in trace elements, particularly with depth. Two of the smaller suites, from the Powell-Rouyn quartz vein, Quebec, and the flow-type ore of Kerr Addison, Ontario, covered a vertical range of only 2,500 feet, but more extensive sampling of the Kirkland Lake gold belt over its three mile length, and of one of the larger deposits in the Porcupine district, Ontario, allowed the study to be extended to depths of over 5,000 feet.

For the most part, study of trace elements present has been made by comparisons of log intensity ratios determined from analytical lines and suitable iron lines as internal standards. In addition, quantitative determinations of cobalt and nickel in the pyrite have been made by acceptable spectrographic procedures.

Factors having a possible effect on trace element composition, which have also been studied in some of the deposits, include variations in size of grain, temperature recordings as made by Dr. F. G. Smith with electrical and decrepitation methods, host rock or matrix, distance from intrusive quartz-porphyry contacts, and occurrence in different veins or ore bodies.

Study of polished sections of pyrite from the different deposits shows varying degrees of purity, and the impossibility of picking pyrite entirely devoid of inclusions of both gangue and other metallic minerals. In each of the deposits visible gold may be found as minute inclusions, stringers, or outer coatings on pyrite, and it is clear that most of the gold present has been introduced after deposition of the pyrite. An effort was made, however, to select pyrite for analyses as free as possible from any visible inclusions. That success was not attained in this is shown by the spectrographic analyses, which in general confirm the erratic distribution of gold in pyrite, and indicate that only by averaging results of many analyses can any significant trends in composition be ascertained.

Trace elements studied in particular include: Au, Ag, Te, Ni, Co, Pb, Zn, Sn, Mo, Mn, Cr, Ti, V, Bi, and As. In most deposits wider variations were

noted in Au, Ag, Ni, Co, Ti; moderate variations in Pb, Sn, Mn, and Cr, and only minor ones in Mo, V, and Zn.

Qualitative differences in trace elements in pyrite of the different deposits consist chiefly of the presence of tellurium in all samples from the Kirkland Lake area and its rarer occurrence in others, whereas arsenic is not detectible in Powell-Rouyn samples and tin, arsenic, and zinc are rare or absent in the Kirkland Lake samples.

Percentages of cobalt and nickel in all pyrite studied show the same variation from 0.02 to 0.10 for each. Kirkland Lake pyrite contains greater amounts than the others, while the pyrite from Porcupine giving only low temperature recordings shows the lowest amount of each. Ratio of Co : Ni in pyrite from Powell-Rouyn, Lake Shore and "low" type pyrite from Porcupine is about 1 : 2, but "high" type pyrite from the latter contains more Co than Ni.

In three of the four deposits the only consistent variation in composition of pyrite *with depth* appears to be a slight increase in cobalt. In individual deposits other elements such as gold and silver, appear to decrease somewhat at depth, nickel, to increase, and others to remain fairly constant, or vary in behavior, but in no case are the variations large nor do they appear particularly significant. In the Kerr Addison deposit, however, examined only to a depth of 2,500 feet, a rather marked increase in gold and silver on the lower levels is of interest. Otherwise, particularly in the deeper deposits examined, average analyses suggest uniformity of conditions of mineralization to depths of over 5,000 feet except where local variations in rock type and structure have had some influence.

Despite the fact that no very definite trends have been indicated in the composition of pyrite with depth, several other points of interest have come from the investigation.

Variations in composition with differences in grain size of pyrite in single specimens, as in Powell-Rouyn and Porcupine samples, may be pronounced even though contained in the same matrix and giving similar (high) temperature effects. Such differences may, however, be ascribed to factors other than actual size of grain such as degree of replacement of the host rock, and/or, later infiltration of certain constituents. Titanium in pyrite at Kirkland Lake thus clearly reflects replacement of magnetite-ilmenite intergrowths, and higher gold of some fine pyrite, compared with coarse, may well be due to its later introduction. On the other hand, uniformity of composition of as many as seven minor constituents in similar sizes of pyrite in some samples of both quartz and wall rock (Porcupine area) gives adequate proof of contemporaneity of deposition of the pyrite in both vein and adjacent rocks, confirmation of which is most difficult to come by in any other way in paragenetic studies. In other cases, where composition varies, no such conclusion is possible.

The relation between trace elements in pyrite and temperature recordings made by F. G. Smith has been studied to a minor extent in connection with two of the deposits, Powell Rouyn and Kerr Addison, but in considerably more detail on pyrite from the Porcupine area. Pyrite from the Powell Rouyn vein, giving temperature readings of 426 to 520° C falls in one temperature class, but

varies widely in such constituents as gold and silver showing both high and low values, indicating no temperature control and that these metals could be deposited with the pyrite or introduced later regardless of initial temperature of deposition.

A few specimens from Kerr Addison, tested in this manner giving readings of about 300° C to 450° C ± 50° C with a few at the lower temperature of 175° C, suggest in one case that higher gold and silver may be due to its introduction at the lower temperature, though elsewhere low temperature readings may be obtained in pyrite showing no such enrichment in gold.

The more detailed studies of pyrite from the Porcupine area where pyrite giving low, high, and both low and high temperature recordings however, do indicate a relation between these and its composition. Pyrite showing only low temperature effects on the whole, is richer in gold, silver, arsenic, lead, and zinc but poorer in cobalt, nickel, and in some veins in tin, than that giving high temperature readings. Since cobalt and nickel are likely present chiefly in solid solution in the pyrite, their variation is considered directly related to temperature of deposition. In the case of gold and silver, however, the relation to temperature recordings is more complex. Analyses show that all types of pyrite contain at least trace amounts of gold, believed original with the pyrite. Pyrites giving low or high temperature readings contain equally high ratios in gold and silver, but the "low" pyrite, on the average, contains larger quantities than the "high" pyrite. Since there is no evidence for more than one main period of gold deposition, the bulk of the gold, as shown also by polished sections, is considered to have been introduced into the pyrite after its original deposition, that giving only low temperature readings, acting as the better precipitant, due to either original or imposed structural characteristics. Single grains of pyrite giving both high and low temperature readings agree in trace element composition with that showing only high readings, except for its higher arsenic content which probably reflects a low temperature effect. No particular enrichment in gold or silver, however, can be related to the low temperature readings, and the lack of any low readings in "high" pyrite containing erratic but appreciable quantities of gold, makes it difficult to actually confirm that the gold was introduced at *low* temperatures. If the gold was largely of late origin, as seems well established, by both polished sections and spectrographic analyses, its late emplacement, presumably at low temperatures, in most cases was in such a manner as to give no temperature effects by present methods of measurement, and its distribution appears more related to structural factors, than to original temperature of deposition of the pyrite.

Substantiation of this is found particularly in the Porcupine area where proximity to quartz-porphyry contacts appears as a distinctly favorable feature for greater deposition of gold whether in pyrite showing high or low temperature effects.

Study of variations in pyrite in different veins or ore bodies within individual camps shows only minor outstanding differences, such as high tin in parts of certain veins, and variations in cobalt and nickel in differing wall rocks, though locally the content of other elements may vary considerably, as noted

also by Auger. Notable rather is the uniformity of pyrite particularly of the Kirkland Lake belt over a length of 3 miles to a depth of 6,000 feet.

QUEEN'S UNIVERSITY,
KINGSTON, ONTARIO,
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THE AGE OF THE "LOWER CRETACEOUS" FROM BISBEE, ARIZONA URANINITE.

GEORGE W. BAIN.

ABSTRACT.

Uraninite from the ore deposits at Bisbee, Arizona has an age of 104 ± 6 million years, corresponding to the expectable age for the end of the Lower Cretaceous period. An obscure orogeny and volcanic series in the Southwest have this relative geologic age and are believed to be a part of the important metallogenic disturbance for the Bisbee region. The Sacramento porphyry appears to have been intruded before deposition of the Lower Cretaceous strata, and sericitization of it seems to have occurred after the series was deposited and during the mineralization episode about 104 million years ago. The uraninite is an early mineral in the paragenetic sequence and the hypogene bornite is relatively late. The early uraninite is excluded mechanically during the growth of such later minerals, as pyrite, with high "crystallizing power."

INTRODUCTION.

URANINITE was recovered from several deposits at Bisbee, Arizona and the ratio of radiogenic Pb206 to Pb207 is used to estimate the age of the mineral. The radiogenic age indicates either that the mineralization followed the late Lower Cretaceous disturbance or that the Lower Cretaceous period began much more recently than is generally believed. The general geologic setting indicating the age of the rocks and structures relative to the mineralization, the occurrence of uraninite in the deposits showing the place of uraninite in the mineralization series, and the isotope analysis of both galena lead and mixed lead necessary to calculate the age of the mineral in years, are given to bring out the significance of this occurrence to dating the Lower Cretaceous period, and also some events in the structural history of the southwestern United States and adjacent Mexico.

GENERAL BACKGROUND OF THE PROBLEM.

The principal Bisbee ore bodies lie in the so-called Copper Queen block[1] which is bounded on the north by the Dividend Fault and is made up of Precambrian crystallines, Paleozoic age sediments, and the irregular intrusive mass of Sacramento Hill quartz porphyry. The ores and the quartz porphyry are overlain by Lower Cretaceous sediments; the Glance conglomerate at the base of these sediments contains boulders bearing a general resemblance to Precambrian crystallines, all Paleozoic age sediments, and some quartz porphyry and shows no obvious effects which could be attributed to metamorphism by intrusive quartz porphyry. This appearance has led to interjection of the tacit

[1] Hogue, W. E., and Wilson, E. D., Arizona zinc and lead deposits: Arizona Bur. Mines, Geol. Ser. No. 18, Bull. 156, p. 24, 1950.

assumption that the quartz porphyry, its contact breccia, and the ore have the same age and this has confused the regional history of the southwest. Tenney [2] states that the Sacramento Hill porphyry exposed now is highly altered whereas the boulders of porphyry in the adjacent Glance conglomerate are invariably unaltered. This absence of alteration in the boulders needs additional investigation. The alteration in the porphyry is similar to alteration associated with the ore bodies at their contact with similar rocks. The age of the ore and the ore-making disturbance becomes the age of the alteration and not the age of the porphyry and these two dates may be the same or different. Hogue and Wilson (p. 23) report:

> Material resembling contact breccia—within fissures of the various fracture systems of the district. These breccia filled fissures were identified by G. M. Schwartz as breccia dikes. In places they are mineralized.

The structures certainly resemble breccia dikes and sills and they contain occluded fragments of sulphides as well as porphyry, but their contemporary or post-mineral age is still uncertain and they do not establish any ore-porphyry relationship. If the Sacramento porphyry is later than the Dividend fault and older than the Glance conglomerate, then it is of very early Lower Cretaceous age. If the ore and the porphyry have the same age, then the uraninite would give the age of the Jurassic-Lower Cretaceous boundary. On the other hand, if the alteration of the Sacramento porphyry occurred after deposition of the Glance conglomerate and the conformable Lower Cretaceous strata involved in the recognized post-Lower Cretaceous period of faulting, and occurred as a result of passage of ore-bringing solutions, then the uraninite gives the age of the end (rather than the beginning) of the Lower Cretaceous period. For the time being, it will be well to consider that all evidence is not on record and that age here determined on the basis of radioactive minerals is the best that is available now.

GENERAL GEOLOGIC SETTING.

The critical horizon for geologic dating of the Bisbee ore deposits and structure has been considered to be the Glance conglomerate occurring at the base of the Lower Cretaceous system. The formation occurs on both sides of the Dividend fault. According to Ransome [3] it is thin and relatively uniform north of the Dividend fault but is erratically thick south of it. The Glance conglomerate rests principally upon Pinal schist (Precambrian) north of the Dividend fault and upon Naco limestone (Permian) south of it; locally the conglomerate is in contact with Sacramento porphyry but its relationship is not proven beyond reasonable doubt. Evidently a major part of the movement on the Dividend fault occurred before deposition of the Glance conglomerate, and only a part of the resultant topographic relief had been erased before the gravels buried the pre-Lower Cretaceous fault trace.

[2] Tenney, J. B., Ore deposits of the Southwest: XVIth Internat. Geol. Cong., Guidebook 14, p. 52, 1932.

[3] Ransome, F. L., The Bisbee Folio: U. S. Geol. Survey Folio 112, p. 5, 1904.

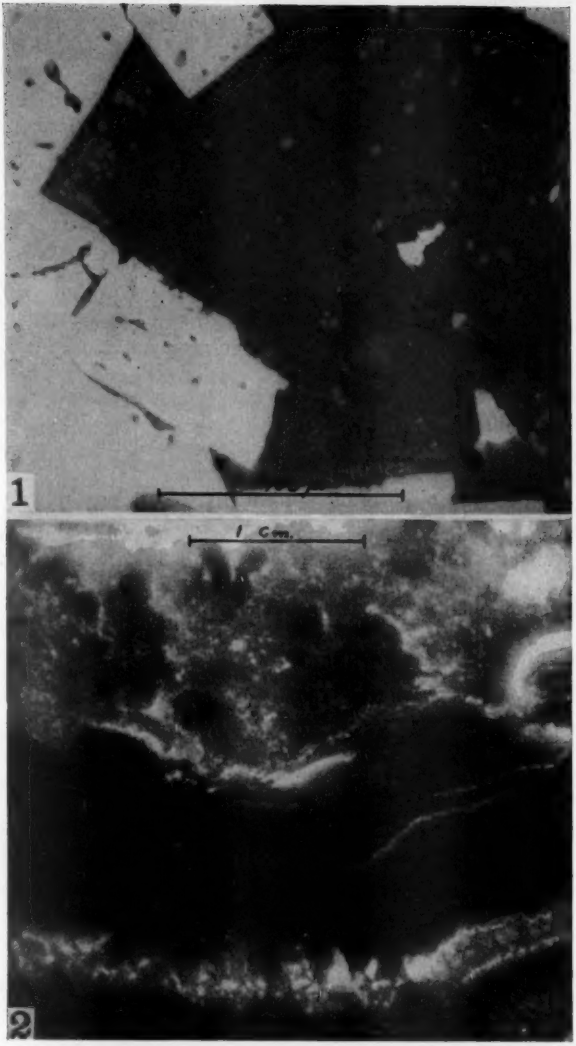

FIG. 1. Uraninite-limestone-pyrite relations. (Reflected light.) Uraninite (light gray squares) is limited to the limestone (dark gray). A narrow pressure fringe separates the pyrite (white) from the uraninite cluster in the angle at the upper left. The uraninite cluster lies along the continuation into the pyrite of a uraninite zone that is parallel to the top of the figure.

FIG. 2. Autoradiograph of polished surface of radioactive ore. The white bands are zones of abundant uraninite cubes. The dark bands are dense fine grained pyrite. The dark areas in the upper part of the figure are later pyrite crystals. Note that the radiation (indicative of uraninite nearby) is normally diffuse but that it is gathered into a dense zone around the coarse pyrite.

The Morita formation overlying conformably the Glance conglomerate is offset about 1,300 feet near the Saginaw shaft by the Dividend fault; at the same place the base of the Bolsa quartzite (Cambrian) is offset not less than 4,500 feet. Concurrent post-Lower Cretaceous movement occurred on other faults of the system, including the Mexican Canyon fault and the Saginaw fault. The evidence of repeated movement at two periods separated by the entire Lower Cretaceous interval leaves indeterminate the date of origin for the ore-bearing fracture systems, and hence of mineralization from structural data. On the basis of existing observations, the age of the ore-making episode relative to the Glance conglomerate becomes merely a matter of individual weighting of the evidence. Hogue and Wilson indicate clearly that the mineralization accompanied a major disturbance in the Mule Mts.; without concurring or dissenting with their assignment of geologic age, the above statement reviews the geologic facts and the ensuing paragraphs give the date in years for this disturbance, which must have been just before or just after the Lower Cretaceous period depending upon weighting of the evidence.

THE MINERAL SEQUENCE AT BISBEE.

Uraninite is almost the earliest mineral in the sequence at Bisbee[4] and the copper minerals represent the closing phases of mineralization with some gold quartz veins representing possibly a later cycle. The intermediate stages show a pyritic phase, a galena-sphalerite phase, and a quartz-carbonate phase. This age problem requires only enough evidence to show first, the position of uraninite early in the mineralization, and second, existence of reasonable continuity to mineralization throughout the formation of the mineral deposits.

The principal uraninite occurs in micron sized cubes along slip planes in the rocks of the Copper Queen block and these slip planes can be resolved into a fracture shear system related to the Dividend fault. Some minute hematite flakes and quartz crystals are associated with the uraninite.

Subsequent pyritization excluded the uraninite to the fringes of the individual pyrite crystals (Fig. 1). Zones of diffuse uraninite cubes are displaced slightly from their original line and are clustered around the pyrite which, by growth, has occupied the position of the original zone (Fig. 2). Some bands had uraninite reorganized into almost continuous groups of cubes around the pyrite to simulate a later encrustation.

Locally the uraninite crusts are broken free from the pyrite and either galena, or sphalerite, or both form intrusive veinlets at the ruptures and sheets along the mineral contacts (Fig. 3). Veinlets of galena and sphalerite contain angular inclusions and crusts of uraninite.[5]

[4] The uraninite is in narrow crosscutting zones through the orebodies and gives the "bulk-appearance" of being in veins later than the other ores. Actually a microscope study, checked back against structure in large ore specimens, showed the uraninite to be merely a refractory residue of an early mineralization that survived, in somewhat shredded and "battered" form, the main base-metal mineralization that enveloped it.

[5] Galena and sphalerite are attributed generally to a stage of mineralization subsequent to copper introduction. Microscopic study of the uraninite specimens showed no copper mineral-

The galena mineralization phase was accompanied by development of some solution cavities and followed by deposition of carbonates and quartz. The carbonates or quartz pseudomorphs of carbonates have crusts of uraninite; tentatively it is inferred that the uraninite could be recrystallized by the solutions of this phase. Quartz commonly occludes uraninite veins and botryoidal

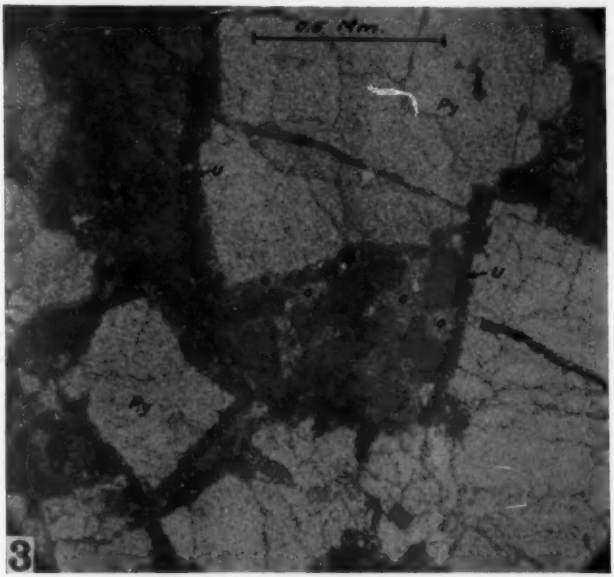

FIG. 3. Galena-uraninite-pyrite relations. (Oblique reflected light.) Pyrite cubes (Py, rough light gray) and limestone (Ls, smooth dark gray) are fractured and crossed by veins of galena (G, medium gray, rough) and quartz (Q, black). Groups of uraninite grains (U, rough black) surround the pyrite. This uraninite zone is breached by the galena-quartz vein in the middle right and has a sheet of quartz and galena introduced behind it to the left of center. The galena-quartz vein, approaching the upper left, has filled an opening between the pyrite receding from the left and the uraninite.

hematite, indicating a capacity of the solutions to wet these minerals and grow around them, but possessing negligible solvent power on uraninite or hematite. (The geochemist may be able to make something of these observations as an

ization between the pyritic stage and the galena-sphalerite stage but did show both chalopyrite and bornite encrusting the galena and sphalerite. Like the uraninite, galena and sphalerite formed some indistinct zones through copper bodies but when subjected to microscope study, their structure showed the galena-sphalerite to be earlier; review of the structure in large specimens confirmed the observations made under the microscope. Possibly the main base metal orebodies may have galena and sphalerite later than the chalcopyrite and bornite, but the evidence is against such an age relationship for the lead zinc minerals of the uraninite zones.

indication of alkalinity of the solutions, using solubility of uranous uranium in alkalies as an index.) The intensity of this nonmetallic phase varies widely in different parts of the Copper Queen block. Principal chalcopyrite-bornite mineralization may have overlapped the nonmetallic phase but a considerable part was subsequent; copper minerals occur as encrustations in the solution cavities wherever these could be identified and studied.

Quartz veins with native gold have been identified cutting chalcopyrite and bornite discordantly. Chalcocite, covellite, bornite, and sphalerite microveins, related to discordant permeable zones, are numerous. All that were subjected to detailed microscope study have supergene associations and reaction structures rather than introduced affinities.

The mineralization sequence appears to be continuous from uraninite to chalcopyrite and through principal bornite. Overlapping of some phases was recognized. No indications of overlapping of uraninite with pyrite was recognized although some of the microbanding of uraninite and fine-textured early pyrite might be so construed. Definitely, no Bisbee ore is older than the uraninite and the uraninite age sets the maximum age for the deposit.

ISOTOPE ANALYSIS OF BISBEE ORES.

Three specimens with abundant uraninite were assayed for uranium and lead; also the isotope analysis of their lead and of the lead in pure galena associated with them was made in the Oak Ridge National Laboratory. The knowledge of the isotope components in the lead of mixed origin, used in conjunction with the isotope analysis of the lead of galena origin, makes possible an approximate estimate of the ratio of Pb206 to Pb207 in the radiogenic lead component.

The isotopic composition of the galena was as follows: (Sample No. 1).

	Pb204	Pb206	Pb207	Pb208
Percent	1.44 ±0.02	24.03 ±0.02	21.71 ±0.06	52.82 ±0.04
Ratio to Pb204	1.00	16.69	15.07	36.68

The Pb 206/207 ratio is 1.125 and falls into the group of Appalachian leads. As will be seen later from the ratio of Pb 206/207 for the radiogenic fraction, the above ratio is due probably to mixture of a Precambrian lead with a Mesozoic ore-producing magma to give a Paleozoic average ratio.

The assays and analysis of the uraninite samples are given in Table I.

TABLE I.

ASSAYS OF URANINITE-BEARING SAMPLES.

Sample	U	Pb	Th	Pb204	Pb206	Pb207	Pb208
2	13.27	13.39	−0.01	1.44 ±0.02	25.25 ±0.05	21.47 ±0.02	51.84 ±0.03
3	16.15	14.21	−0.01	1.43 ±0.008	25.47 ±0.02	21.52 ±0.02	51.58 ±0.01
4	9.84	13.35	−0.01	1.42 ±0.02	25.05 ±0.06	21.46 ±0.04	52.08 ±0.05

The high content of total lead and the normal amount of Pb204 indicate that the samples had about equal amounts of galena and uraninite although the material had been hand picked under a binocular microscope, and had been passed through gravity, magnetic, and froth flotation separators. The extreme minuteness of the individual particles makes complete separation of pure uraninite impractical. Accordingly, certain credible ages were assumed for the uraninite and the amount of total radio-lead for the determined amount of

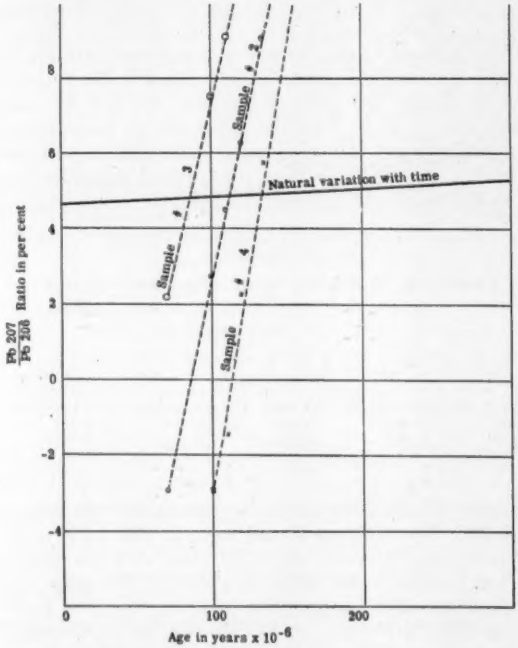

FIG. 4. Pb 207/206 Ratios in percent. The dotted lines show the ratios for Bisbee samples calculated for the different ages within the possible range. The full heavy line shows the ratio variation determined by Nier. The intersection of dotted and full lines gives the probable age of the samples.

uranium was calculated; the Pb 207/206 ratio for the radio-lead which would give the measured mixtures was then estimated by substituting values. All results lying off Nier's graph [6] (Fig. 4), by an amount greater than the experimental error, were considered to be based upon an assumed age, which was impossible.

[6] Nier, A. O., Isotopic constitution of lead: Phys. Rev., ser. 2, vol. 55, p. 157, 1939.

TABLE II.

CALCULATED RADIO-LEAD CONTENT OF SAMPLES IN TABLE I.

Sample	Age in years $\times 10^{-6}$					
	70	100	110	120	135	190
2	.122% Pb	.174% Pb	.192% Pb	.210% Pb	.236% Pb	.332% Pb
3	.149	.212	.234	.255	.287	.404
4	.091	.129	.142	.155	.175	.246

The ores are in strata ranging to as young as lower Permian age and therefore any greater age can be neglected. The Pb 207/206 ratio in percent for this Permian to Recent age range is between 4.6 and 5.0, and any value departing from this by more than the experimental error is based upon an impossible postulated age. The expectable radio-lead content for the samples at the ages listed is given in Table II. The residual galena lead in the samples is estimated by difference and is given in Table III.

TABLE III.

CALCULATED ORE-LEAD CONTENT OF SAMPLES IN TABLE I.

Sample	Age in years $\times 10^{-6}$					
	70	100	110	120	135	190
2	13.268% Pb	13.216% Pb	13.198% Pb	13.180% Pb	13.154% Pb	13.058% Pb
3	14.061	13.998	13.976	13.955	13.923	13.806
4	13.259	13.221	13.208	13.195	13.175	13.104

The calculated Pb 207/206 ratios in percent for the radiogenic lead is given in Table IV. The table shows one value at 100×10^6 years, two values at 110×10^6 years, two values at 120×10^6 years, and one value at 135×10^6 years which are possible. All values in the 70×10^6 years and 190×10^6 years are impossible. The graphical solution of Figure 4 gives the age of sample No. 2 as 112×10^6 years, sample No. 3 as 85×10^6 years, and sample 4 as 134×10^6 years, with the average value at 110×10^6 years. The lower

TABLE IV.

CALCULATED PB 207/206% RATIOS FOR SAMPLES OF TABLE I.

Sample	Age in years $\times 10^{-6}$					
	70	100	110	120	135	190
2	−2.94%	2.71%	4.5 %	6.24%	9.1%	16.8%
3	2.19	7.50	9.08	10.60	13.3	19.4
4	−8.50	−2.90	−1.45	2.29	5.75	11.5
Average	−3.08	2.44	4.04	6.38	9.38	15.9

accuracy of the lead isotope determinations for sample No. 4 and the lesser amount of radio-lead involved give data from this sample lowest dependability.

THE GEOLOGIC AGE OF THE URANINITE.

The absolute age of the uraninite should be regarded as approximately 110×10^6 years if all samples are given equal value and 98×10^6 years if only the two most dependable determinations are taken into account. These figures are in close agreement with a recognized disturbance and a volcanic episode in southeastern Arizona and adjacent Mexico, which episode is attributed to early Upper Cretaceous time. Ross,[7] Taliaferro,[8] and Stoyanow[9] all report lavas and pyroclastics lying unconformably over Lower Cretaceous strata, and conformably below strata containing Montanan group dinosaurs and Coloradoan group molluscs. This disturbance and volcanic episode is recorded in every occurrence of Upper Cretaceous age strata west of the Santa Rita Mts. of New Mexico and in areas from north of Morenci in Arizona to far south in Sonora, Mexico. The conglomerates associated with the volcanics are said to contain boulders of every formation from the Morita (Lower Cretaceous) down to the Precambrian crystallines. Consideration of the thickness of the Lower Cretaceous strata in southern Arizona assigns to this disturbance an intensity as great locally, as that of the late Jurassic, and deserving of more attention that it has received heretofore.

The best opinion available assigns an age of 130×10^6 years to the beginning of the Cretaceous period and 60 to 70×10^6 years to its close.[10] No possible age value for the Bisbee uraninite, calculated from data supplied by isotope analyses, falls within reach of the time limits of either beginning or end of the Cretaceous period. The values do conform to the usual assumed age of the time interval represented in the widespread break in the stratigraphic record between Lower and Upper Cretaceous systems of strata.

The determined radioactive age seems to leave three choices:

1. The analyses or the statement of them is in error.
2. The Cretaceous period has a much shorter duration than has been assigned to it.
3. The weighting of evidence indicative of age of the Bisbee ore relative to the Glance conglomerate needs revision.

Each of these possibilities is considered below.

The analyses were done with greatest possible care and realization that they would be subject to criticism. There is every reason to believe that the results represent as great accuracy as can be obtained, and the internal evi-

[7] Ross, C. P., Geology and ore deposits of the Aravaipa and Stanley mining districts, Arizona: U. S. Geol. Survey Bull. 763, pp. 27–28, 1925.

[8] Taliaferro, N. L., An occurrence of Upper Cretaceous sediments in northern Sonora, Mexico: Jour. Geology, vol. 41, pp. 25–28, 1933.

[9] Stoyanow, A., Lower Cretaceous stratigraphy, southeastern Arizona: Geol. Soc. America Mem. 38, pp. 59–60, 1949.

[10] Marble, J. P., Report of the Committee on measurement of Geologic Time, 1949–50: Nat. Research Council, p. 18, 1950.

dence from use of maximum estimated limit of error does not shift the age determination to either limiting value for the Cretaceous period as it is now assumed to be dated. This possible defect in the age determination has no basis.

The Laramide disturbance has been dated fairly closely by a large number of independant determinations. This disturbance is generally accepted as the cause for the very widespread break in the record between the Mesozoic and Cenozoic eras. The Nevadan-Mongolian revolution occurred almost at the close of the Jurassic period; unfortunately only helium radiometric ages for rocks attributed to this episode are available and the helium ages, at least those determined on granitoid rocks without special treatment, have been low by comparison with other methods. Larsen and Keevil [11] give a tentative age for the California batholith at 120 to 135 $\times 10^6$ years and Hurley and Goodman [12] give 120 to 130 $\times 10^6$ years for magnetite of the same locality. These determinations indicate that the Lower Cretaceous period began not less than 120 $\times 10^6$ years ago and probably at least 135 $\times 10^6$ years ago. Thus the age of the Bisbee uraninite falls about midway between previously determined age limits for Cretaceous time.

The opinion that Bisbee ore is older than the Glance conglomerate leaves the reputed absence of alteration in the quartz porphyry boulders inadequately explained. Ransome [13] recognized some movement on the Dividend, fault and many other faults, as having post-Lower Cretaceous age. The slight amount of crushing and slickensiding in Bisbee ore and continuity of some sulphide masses across faults are not commensurate with the magnitude of movement during and since Lower Cretaceous time. It seems that too much weight has been placed upon first, the supposed Glance conglomerate-Sacramento porphyry nonconformable relationship, and second, upon derivation of the ore from the Sacramento Hill porphyry rather than upon introduction by the solutions which altered the porphyry. The opinion concerning the age of the Bisbee ores is based more upon geologic faith than upon physical fact and would seem to admit of necessary substantial revision.

CONCLUSION.

The uraninite in the Bisbee ores suggests an age of 85 to 112 million years. This mineral age appears to correspond with a disturbance for Arizona and adjacent Mexico, recorded by a nonconformity and volcanic formations representing late Lower Cretaceous and early Upper Cretaceous time.

ACKNOWLEDGMENTS.

The writer wishes to express his thanks to the Phelps Dodge Corporation, particularly the members of the Copper Queen Branch, for assistance in con-

[11] Larsen, E. S., and Keevil, N. B., Distribution of helium and radioactivity in rocks: Am. Jour. Sci., vol. 240, p. 212, 1942.

[12] Hurley, P. M., and Goodman, C., Helium age measurements: Geol. Soc. America Bull., vol. 54, p. 305–324, 1943.

[13] Ransome, F. L., The Bisbee Folio: U. S. Geol. Survey Folio 112, p. 9, 1904.

ducting the field study of the ore bodies, and for release of this part of the investigation. The U. S. Atomic Energy Commission supported the field study, made the essential analyses and the isotope separations without which no estimate of absolute age would have been possible. This sort of assistance to scientific investigation offers great advantage to solution of at least the intricate age problems of mineral deposits where even minute amounts of uraninite exist with the ore.

AMHERST COLLEGE,
AMHERST, MASS.,
Nov. 15, 1951.

GEOLOGIC AND ECONOMIC SIGNIFICANCE OF THE HUTSON ZINC MINE, SALEM, KENTUCKY—ITS RELATION TO THE ILLINOIS–KENTUCKY FLUORSPAR DISTRICT.

W. A. OESTERLING.

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ABSTRACT.

A zinc sulphide deposit, almost unique for the district, is being worked at the Hutson mine in the Southern Illinois-Western Kentucky fluorspar district. A lode-fissure with flanking massive replacement deposits is present. The ore is remarkably high-grade with no fluorspar or galena values and is associated with mica-peridotite dikes.

There is evidence that the sphalerite mineralization at the Hutson mine was later than the main calcite-fluorite-sulphide mineralization in the district. Some late sphalerite and galena are found in the major fluorite veins in the district but deposits of late sphalerite only, which are of economic importance, have been exceptionally rare.

The Hutson mine offers a key to the structural and mineralogical history of the Illinois-Kentucky fluorspar district. A six-fold sequence of geologic events is indicated and is supported by evidence in other mines of the district.

INTRODUCTION.

Location and Topography.—The Hutson mine is located near the southern edge of the complexly faulted Southern Illinois-Western Kentucky fluorspar

district, three and one-quarter miles southwest of Salem in Livingston County, Kentucky. Salem is located on U. S. Highway 60 between Marion and Smithland.

The most prominent topographic features in the maturely eroded district are fault-line scarps of moderate relief. Sandy Creek drains the land in the vicinity of the mine and flows into the Cumberland River three miles south.

Significance.—Although the major fluorspar deposits in the district contain some zinc and lead sulphides, the Hutson is the only property, at present, where zinc sulphide alone is mined.[1] Three other mines in the district, all in Kentucky, have produced only zinc ore. None have been developed to any appreciable extent and none are producing at present. The bulk of the ore from these mines was in the form of zinc carbonate.

The remarkably high-grade Hutson zinc ore is associated with mica-peridotite dikes but is not a product of differentiation of the dike material. The presence of the dikes, however, manifests the complete sequence of geologic events that led to the formation of the zinc sulphide; (1) pre-dike fracturing, (2) basic dike intrusion, (3) major block faulting, (4) calcite-fluorite-sulphide mineralization, (5) post-fluorite faulting, and (6) late stage sphalerite mineralization. There has been faulting after the deposition of the late sphalerite, chiefly as minor movements along nearly horizontal bedding planes. This sequence is supported by evidence in other mines of the district, and represents a summary of the structural and mineralogical history of the Southern Illinois-Western Kentucky fluorspar district. The complete sequence of geologic events is rarely evident in a single mine.

Aside from its own economic value the significant economic feature of the Hutson zinc deposit is, of course, that it indicates the probability that other similar deposits of late-stage zinc sulphide are present in the district. Zinc is a vital mineral in the nation's economy for which the United States must rely greatly on imports to fulfill its industrial needs. In 1944, one of the most productive years for the district, only 5,910 short tons[2] of recoverable zinc were produced, all as a byproduct of fluorspar mining and milling. This amount represented only 0.85 percent of the total U. S. production for that year.

According to R. L. Wilcox,[3] Chief of the Nonferrous Metals Branch of the Economic Cooperation Administration, "Mine production in the U. S. in terms of recoverable zinc continued its downward trend of the last few years and in 1949 failed to meet smelter requirements by an indicated 261,000 metric tons." Contributing largely to this decline in zinc production has been the gradual depletion of the zinc reserves in the Tri-State district which is still by far the greatest zinc mining area in the United States. Charles R. Ince[4] states "nearly 400,000 tons of imports would be required in 1951 to maintain

[1] Only two small seams of galena have been found in the mine. No galena was cut by diamond drilling.

[2] Mineral Resources of the United States, U. S. Bureau of Mines and U. S. Geological Survey, p. 208, Public Affairs Press, Washington, D. C., 1948.

[3] The Current World Zinc Situation, an address presented at the 32nd Annual Meeting of American Zinc Institute, Inc., St. Louis, Mo., April 12, 1950.

[4] Ince, Charles R., Metals in Review—Zinc: Eng. and Min. Jour., pp. 84–86, Feb., 1951.

smelter capacity. . . ." He estimates smelter capacity in 1951 at about 1,000,000 tons of metal. This is 110,000 tons short of total demand in this country during 1950. These facts emphasize the great need for a sharp increase in zinc production which can be accomplished most effectively by the discovery and development of new deposits. The Southern Illinois-Western Kentucky district may be the future source for a significant portion of this necessary increase.

FIG. 1. The Hutson mine in respect to the So. Illinois-W. Kentucky fluorspar district.

History of Mining and Exploration.—Between 1914 and 1945, about 53,000 tons of 40 percent zinc ore, 30,000 tons of carbonate, and 23,000 tons of sulphide, are reported to have been mined from the Hutson. In 1946, the property was purchased by the Aluminum Ore Company, a subsidiary of the Aluminum Company of America. The Aluminum Ore Company diamond drilled the property in 1947 and discovered new vein and replacement ore beneath and beyond the old workings. In January, 1949, the Alcoa

Mining Company, also a subsidiary of the Aluminum Company of America, took over the operation of the Hutson mine. A new 523 foot shaft has been sunk and crosscuts driven to the vein. New levels at 300 and 425 feet are being worked.

The old mine workings consist of levels at 90 feet, 140 feet, and 200 feet and an open cut about 200 by 400 feet from which considerable zinc carbonate was taken. Only the 200 foot level is now accessible. The 90-foot level was a room 105 by 145 feet located beneath the open cut. Most of the ore mined from this room was probably carbonate. Eight hundred feet of drifting was done on the 140 foot level, 260 feet on the main vein. Two shafts, both now caved, were sunk to the 140 foot level and a raise was driven to the room above. About 1,450 feet of drifting was done on the 200 foot level, 930 feet on the main vein. Mostly zinc sulphide but some carbonate was mined from the stopes above this level. The workings on the 200-foot level are accessible through both the new shaft and the old main shaft.

GENERAL GEOLOGY.

Local Structure and Stratigraphy.—Within a one mile radius of the Hutson mine are faulted rocks of Mississippian and Pennsylvanian age (Fig. 2). The Mississippian strata, listed oldest to youngest, include the St. Louis limestone and Ste. Genevieve (Fredonia limestone, Rosiclare sandstone, and Levias limestone) formations of the Valmeyer Series; the lower Chester Renault limestone and shale, Bethel sandstone and Paint Creek shale and sandstone; the middle Chester Cypress sandstone and shale; and the upper Chester Menard limestone and shale, Palestine sandstone and Clore, Degonia and Kinkaid limestones, shales and sandstones. The Pennsylvanian rocks are represented by the Caseyville conglomerate.

The host rocks for the zinc ore are the St. Louis and Warsaw limestones. The St. Louis is dark gray, fine to medium grained with many chert beds and nodules, and occasional shale partings. Locally there are light gray, medium crystalline beds, and thin oölitic layers. The Warsaw is similar but with less chert and is generally darker and more argilaceous.

Faults.—The ore occurs in a fault block of the St. Louis limestone with Ste. Genevieve outcropping on the higher ground. This fault block is tilted two or three degrees northwest and is bounded on the west by the northeast trending Sandy Creek fault system and on the east by the northeast striking Moore Hill faulting (Fig. 2). The east fault of the Sandy Creek zone, which drops the Ste. Genevieve against the St. Louis, crosses the Hutson property about 500 feet west of the mine. Its exact location in the vicinity of the mine is not now known. Three nearly parallel footwall splits from this fault strike about N 55° E across the property toward north-south trending dikes described below. Two of these minor faults definitely offset the dikes. The third, apparently dying out, fractures the west dike and terminates against the east dike. About 7,000 tons of 80 percent fluorspar are reported to have been mined from shallow veins on these faults.

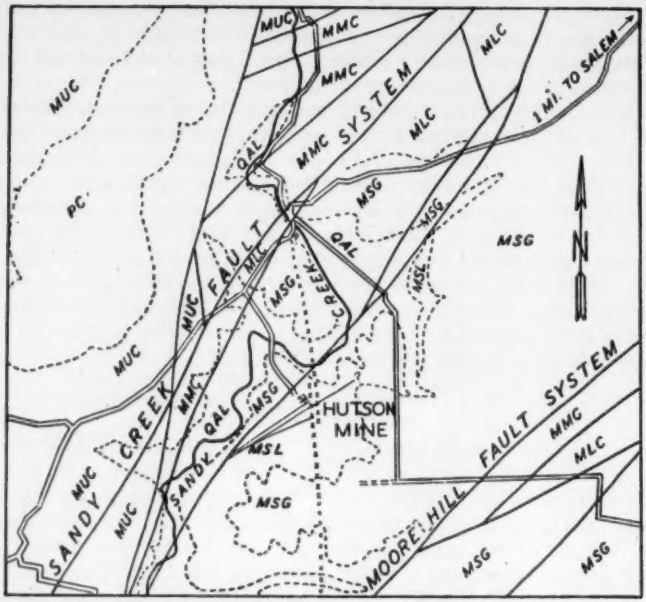

FIG. 2.

Successively toward the west across the Sandy Creek fault system, the middle Chester formations are faulted against the Ste. Genevieve and the upper Chester against the middle Chester formations. In the area one mile east of the Hutson Mine the Moore Hill faulting has dropped the Cypress sandstone against the Ste. Genevieve formation.

Dikes.—A pair of subparallel, mica-peridotite dikes striking N 5° W are exposed in the mine (Fig. 3) and have been cut by diamond drilling at various places. The dikes are 110 feet apart on the 200-foot level measured along the crosscut from the new shaft to the vein, and 84 feet apart in the 425-foot level crosscut directly beneath the 200 level crosscut. Both dikes dip steeply to the east. The east dike dips on the average about 86 degrees and the west dike about 80 degrees between the 200- and 425-foot levels. They have been faulted and fractured by horizontal movement along planes nearly parallel to the dikes and have been offset by later, post-sphalerite faulting along bedding planes in the nearly horizontal St. Louis limestone which has resulted in variations from the general dip. They have also been offset by the major faulting in the district which preceded both phases of the horizontal faulting (Fig. 3). The east dike outcrops at the surface along the east face of the open cut where it has weathered to a loose, dark greenish-brown mica dirt.

A striking characteristic of the Hutson dikes, observed in the mine and in drill cores, is that both light green and dark green colors are present. The light green portions of the dikes are distinctly related to the mineralized areas. For example, the west dike on the 200-foot level, where cut by the southwest drift at coordinate 7775 north, is faulted along a nearly vertical plane within and parallel to the dike (Fig. 3). The fault is filled with a clay-like gouge and the dike on the east side of the fault, facing massive replacement ore, is light green and very fine-grained while on the west side of the fault it is dark green and medium grained. Four diamond drill holes located further south showed the same relationship between the light green and dark green portions of the west dike.

On the 425-foot level a drift is being driven south along the west dike which carries up to one foot of sphalerite in a vein within the dike near its east side. The dike is 8 to 9 feet wide. The portions of the dike adjacent to the vein have been altered to a light green very fine-grained rock which grades west into dark green medium-grained dike (Fig. 4).

Further illustration of this point is given by the relatively narrow east dike with which the bulk of the zinc ore is associated. Thus far, throughout the mine the east dike is light green and very fine-grained with the exception of the dark green center of the thicker part of the dike north of coordinate 8210 north (Fig. 3).

It is obvious that the light green, fine-grained portions of the dikes are the result of hydrothermal alteration of the originally dark green intrusives. This conclusion is strengthened by examination of thin sections of the dikes. Thin sections prepared from the dark green portion of the west split of the east dike at coordinate 8210 north on the 200-foot level and from the central, dark green portion of the west dike on the 425-foot level crosscut, show about 60 percent of the rock is made up of phenocrysts of altered pyroxene and olivine, shreds of phlogopite and accessory iron-titanium oxide, iron sulphide, and iron oxide. An extremely fine-grained groundmass of calcite with some chlorite composes the remaining 40 percent. Tiny apatite needles are fairly abundant both in the groundmass and as poikilitic inclusions in the phlogopite. There

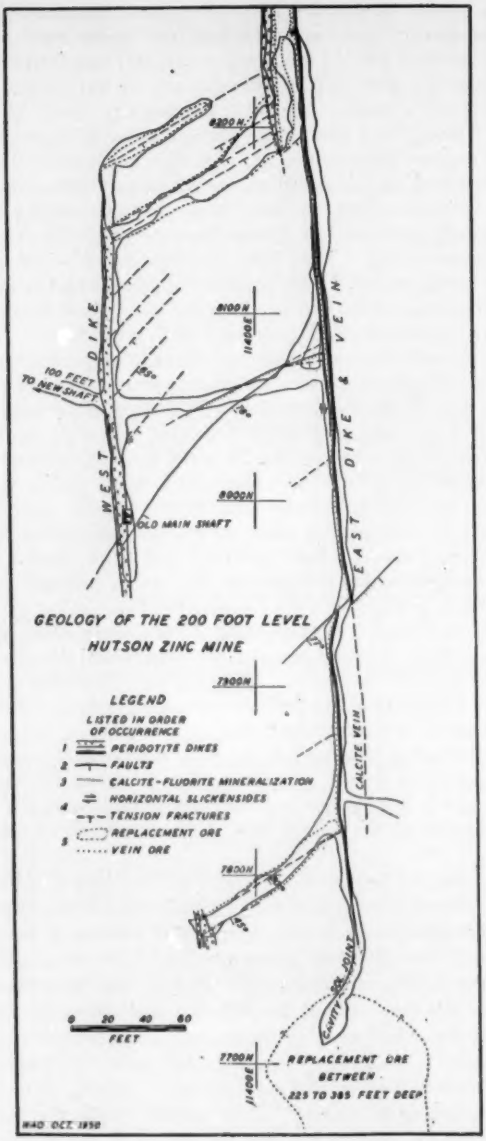
8200 N
8100N
11400E
WEST DIKE
EAST DIKE & VEIN
100 FEET TO NEW SHAFT
OLD MAIN SHAFT
8000N
GEOLOGY OF THE 200 FOOT LEVEL
HUTSON ZINC MINE
7900N
LEGEND
LISTED IN ORDER OF OCCURRENCE
1 PERIDOTITE DIKES
2 FAULTS
3 CALCITE-FLUORITE MINERALIZATION
4 HORIZONTAL SLICKENSIDES
TENSION FRACTURES
5 REPLACEMENT ORE
VEIN ORE
CALCITE VEIN
7800N
CAMPBELL SHAFT
0 20 40 60
FEET
7700N
11400E
REPLACEMENT ORE BETWEEN 225 TO 385 FEET DEEP
WAD OCT. 1950

FIG. 3.

FIG. 4. Effects of hydrothermal alteration of the west dike on the 425-foot level, looking south, and shows from left to right the east contact between light green dike and black jasperoidal Warsaw limestone; four inches to one foot of altered dike; vein of calcite and sphalerite eight inches to one foot wide; up to two feet of light green altered dike with dark green dike beyond. Rule shows four feet.

FIG. 5. Looking north at lode-fissure where cut by 425-foot level crosscut. The nearly vertical aluminum paint lines mark approximate extent of coarsely crystalline, very pure sphalerite. Contacts of replacement sphalerite and marcasite with wall rock are shown by the convex paint lines. East dike is entirely replaced. One foot of downthrow to the east is apparent.

are minute traces of quartz anhedra, either secondary or zenolithic, most with wavy extinction and in ragged contact with the calcitic groundmass. Phlogopite makes up an estimated 25 percent of the dike, altered pyroxene and olivine about 20 per cent, and the opaque accessories magnetite, ilmenite (in part altered to leucoxene), hematite, and pyrite about 15 percent. The phlogopite is typically shredded along the cleavages, is pleochroic from colorless to light reddish-brown, and shows partial replacement by the calcitic groundmass. Most of the phlogopite shreds are about 230 microns or less in length, the longest being 0.5 millimeter. The subhedral to anhedral phenocrysts of olivine and pyroxene have been replaced by calcite which is generally much coarser-grained than that of the groundmass. Although original crystal outlines are only occasionally apparent, several grains display typical olivine outlines and others definite clinopyroxene faces. Most of the olivine and pyroxene grains are within a size range of 170 to 860 microns, the largest being a sub-rounded grain 2.4 by 2.6 millimeters, probably pyroxene originally.

Thin sections of the light green portions of the west split of the east dike at coordinate 8210 north on the 200-foot level are composed nearly entirely of fine-grained calcite. The phlogopite has been completely replaced by calcite; there is no indication that olivine or pyroxene phenocrysts were ever present, and the ilmenite is entirely altered to leucoxene. The apatite prisms remain.

Johannsen [5] did not have the opportunity actually to observe the dikes in the field, but from thin section studies in 1905 he classified the dikes of the Illinois-Kentucky fluorspar district as mica-peridotites and lamprophyrs. Johannsen distinguished the lamprophyrs from the mica-peridotites by the presence of olivine in the peridotites, and reported nearly all of his lamprophyr slides to be characterized by "a remarkable and unusual occurrence of apatite" in the form of large, stubby, perfectly fresh prisms. His description of the lamprophyrs follows, and is of interest since it could appropriately fit slightly less altered dike rock than is described above from the Hutson mine. ". . . the original minerals are so much altered to calcite that subdivision is impossible, for in no case is there any of the feldspar remaining. It is possible that there was originally no feldspar, although the disposition of the particles and replacement products seems to point in some of the thin sections to a groundmass originally of lath-shaped crystals." It seems quite possible that Johannsen's feldspar-ghosts may have actually been mica-ghosts. If this is true Johannsen's lamprophyrs could in reality be altered mica-peridotite.

Currier,[6] in 1923, described the igneous occurrences in the Kentucky portion of the district, classifying them as "belong(ing) to the general class of peridotites." Both he and Johannsen gave similar descriptions for the mica-peridotites which would fit very well the relatively fresh portions of the Hutson dikes.

The St. Louis limestone in some places has been altered to a bluish-white

[5] Bain, H. Foster, The fluorspar deposits of Southern Illinois: U. S. Geol. Survey Bull. 255, pp. 28–30, 1905.

[6] Currier, L. W., Fluorspar deposits of Kentucky: Kentucky Geol. Survey, series six, vol. 13, p. 32, 1923.

marble at the dike contacts, and there is considerable black jasperoid adjacent to the dikes in other places (Fig. 4). This recrystallization and silicification generally affects the wall rock to a depth of less than one foot from the dike contacts. In many instances there is no indication of metamorphism of the limestone.

The northward continuation of the east dike has been proved by drilling and test pitting to a point nearly three-quarters of a mile north of the Hutson mine, near the intersection of the dike with one of the Sandy Creek faults (Fig. 2). Its extent beyond this fault has not been determined. To the south the east dike pinches out near the face of the south 200-foot level but extends beyond this point on the 300- and 425-foot levels.

The west dike on the 200-foot level pinches out about 180 feet north of the old main shaft and was not cut by any drill hole north of this point. However, the west dike is very strong to the south. It was ten feet wide at a depth of 300 feet in a drill hole 340 feet south of the old main shaft, and five feet wide at a depth of 180 feet in another hole 485 feet south of this shaft. The southern extent of the dike is not known but dike rock has been cut by diamond drilling on a property nearly one mile south of the Hutson mine.

Description of the Ore.—The sphalerite is light brown to brownish-black, marmatitic, and is associated with considerable marcasite and calcite. Bands of alternating light brown and dark brown sphalerite, apparently due to variations in iron content, have been observed marking successive growth stages of crystals. The ore is mostly fine-grained and commonly vuggy but coarsely crystalline sphalerite occurs as a fissure-filling in places along the vein and in tension fractures.

Both vein and massive replacement ore are present. The bulk of the ore is in a lode-fissure[7] type of vein associated with the east dike. The lode-fissure lies generally along the west side of the dike but occurs locally on the east side, on both sides, and rarely within the dike. Small amounts of ore, mostly carbonate, have been mined from along the west dike above the 140-foot level but no ore was found by diamond drilling along this dike.

Massive replacement ore extends toward the southwest from the lode-fissure along tension fractures between the two major dikes. This type of ore has been taken from stopes above the two northeast trending drifts on the 200-foot level between coordinates 8150 and 8215 north. The smaller, northern deposit was almost entirely zinc carbonate whereas the larger one was high-grade zinc sulphide. These deposits extended to the surface where they have been mined as carbonate from the open cut. A third similar sulphide body has recently been discovered and worked in the vicinity of 7800 north on the 200-foot level, and a number of others are present on the 300- and 425-foot levels. The west dike limits the western extent of the ore in all of these massive replacement deposits that have thus far been worked except one on the 300-foot level. Here the ore extends about 10 feet west of the dike which has been much faulted and altered to a clay-like substance com-

[7] Classification and terminology after Bateman, Alan M., Economic Mineral Deposits, 2nd Edit., pp. 152, 364, John Wiley & Sons, New York, 1950.

posed of a one-layer mica, anatase, and a little apatite and sulphide.[8] A relatively large replacement body was found by diamond drilling below and south of the old works. This ore body is described in detail later.

On the 200-foot level between coordinates 8190 and 8315 north there are two components of the east dike that converge with depth and to the north. These dikes are separated by as much as fifteen feet of limestone and vein ore. The vein ore is present along the inside face of each dike and there has been extensive replacement of the limestone between the veins (Fig. 3).

Character and Extent of the Vein Ore.—The lode-fissure (Fig. 5) consists of banded sphalerite and marcasite with occasional ragged patches of coarse calcite, clearly remnants of an early calcite mineralization which has been nearly completely replaced by the sphalerite and marcasite. Normally there is a band of coarsely crystalline, very pure sphalerite of varying width near the center of the vein which is probably a true fissure filling. This pure band generally does not exceed two feet in width, normally being only a few inches, and is bordered on both sides by alternating bands of marcasite and sphalerite which in turn are flanked by a finer-grained mixture of replacement sphalerite and marcasite with minor amounts of pyrite (Fig. 5). Although sinuous, the contacts between massive replacement ore and wall rock are remarkably sharp, marked by scalloped fractures in the walls developed during the horizontal movement along the dike. Replacement of dike and wall rock has contributed the bulk of the vein ore. In many places the east dike is completely replaced. The lode-fissure varies in width from two or three inches to at least 30 feet, rarely pinching-out completely except at its extremities.

Nine diamond drill holes cut vein ore with a total horizontal width of 62 feet averaging 24 percent metallic zinc. In general the drilling indicated the narrower the vein the better is the grade of ore. This can be demonstrated by two drill holes each showing the extremes of both vein width and grade: Hole No. 2 cut the vein where it was only 2.3 feet wide but assayed 50 percent metallic zinc. Hole No. 56 cut a 19-foot vein width assaying only 9.8 percent zinc. The graph (Fig. 6) shows the deviation of the other seven holes that cut vein ore with respect to the line representing the concept that assay is inversely proportional to vein width. Hole No. 17 was the only outstanding exception to this concept, having a vein width of 15 feet which assayed 39.25 percent metallic zinc.

From the north face of the old 200-foot level to the southernmost ore hole is a distance of 1,100 feet. This does not, of course, represent the maximum length possible for the vein. A six-foot vein width assaying 18 percent zinc was cut at a depth of 565 feet below the collar of the new shaft. This is the deepest test made to date.

Vertical displacement along the lode-fissure probably does not exceed one foot. Although Fig. 5 shows the east wall has been down-dropped, the reverse has also been observed. Since the pre-zinc movement along the dike

[8] Analyzed by X-ray diffraction by W. F. Bradley, Chemist and Head of X-ray Division, Illinois Geological Survey, Urbana, Illinois.

was strike-slip in character, vertical displacements might reasonably be expected to be inconsistent if present at all and may be due in part to undulations of bedding planes. The maximum horizontal displacement thus far measured is three feet. Post-zinc movements along bedding planes have offset the lode-fissure in places. This faulting is described later.

Character and Extent of the Replacement Ore.—Massive replacement ore was found by diamond drilling west of the lode-fissure (Fig. 3). Develop-

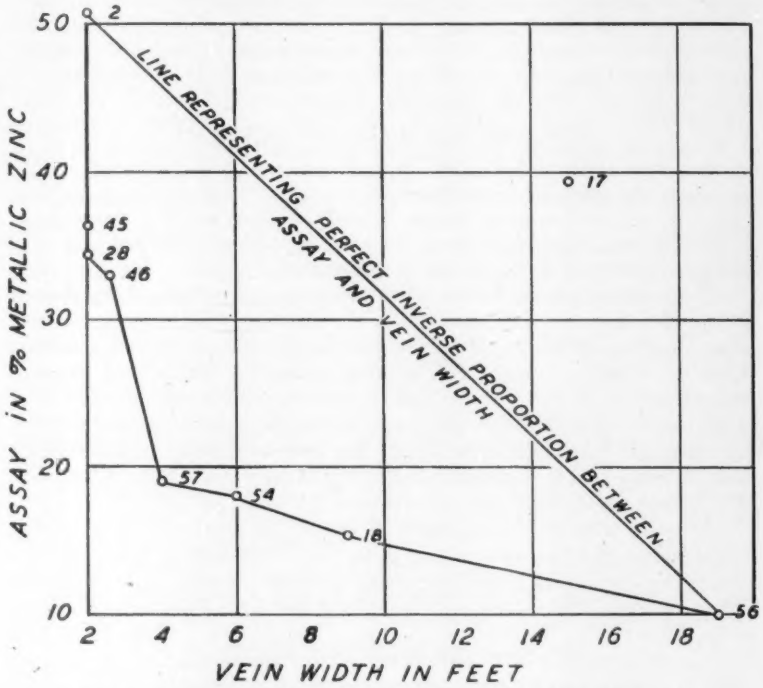

FIG. 6. Graph showing relationship between vein width and grade.

ment work shows this ore follows steeply dipping tension fractures which strike about south 30° west between the two main dikes.

At the present stage of development the replacement ore bodies appear to vary from about 3 to 50 feet wide. In the 300-foot level south drift along the lode-fissure a number of replacement ore shoots trending southwest were encountered. These are 3 to 7 feet wide separated by 4 to 6 feet of barren limestone. About 20 feet above the drift these barren areas become mineralized, thus making a zone of replacement ore approximately 50 feet wide

which may extend upward 40 feet or more. Much the same situation apparently exists on and above the 425-foot level south drift, except that the replacement ore shoots are fewer but generally wider than those on the 300-foot level.

Like the vein ore, the replacement ore contains much marcasite and some calcite with minor amounts of pyrite. Six drill holes cut replacement ore totaling 362 feet and averaging 26.5 percent metallic zinc content, which is slightly higher than the average assay for the vein ore. Many drill cores showed silicified horn corals and stylolitic lines to be the only megascopically visible remnants of the massively replaced limestone. Characteristically, the cores showed a sharp cut-off between almost completely replaced limestone and limestone that contained only a few disseminated grains of sphalerite.

STRUCTURAL AND MINERALOGICAL HISTORY.

General Considerations.—The six-fold sequence of geologic events (see introduction) which culminated in the formation of the Hutson zinc ore is in part, and in rare instances, wholly evident in other mines in the district. Therefore, this sequence represents a summary of the structural and mineralogical history of the Illinois-Kentucky fluorspar district.

The major structural feature of the district is a portion of a collapsed dome which is bordered on the north by the Shawneetown-Rough Creek fault zone, a high angle thrust with displacements, according to Butts,[9] of at least 3,500 feet locally. Collapse of the dome caused the major block faulting which trends generally northeast, but is practically east-west in the southeast section of the district. This pattern of the major faults suggests that they are arranged radially about the dome,[10] the theoretical center of which lies a short distance to the south and west of the district beneath the Cretaceous and Tertiary Embayment deposits [11] west of the Tennessee River.

Dikes are fairly common in and northwest of the district occurring within a zone about 15 miles wide and 60 miles long, northwest to southeast, extending southeastward from Harrisburg in Saline County and Omaha in Gallatin County, Illinois, to near Princeton, Kentucky. Dikes and sills north of the district have been cut in coal mines of Saline County [12] and in oil well holes at the Omaha pool.[13] All of the dikes strike a few degrees west of north or about 45 to 90 degrees from the major faults which are definitely later than the dikes. Some volcanic breccia, a few sills, and granite fragments

[9] Butts, Charles, Geology and mineral resources of the Equality-Shawneetown Area: Illinois Geol. Survey Bull. 47, p. 59, 1925.

[10] Weller, Stuart, Geology of the cave in rock quadrangle: Kentucky Geol. Survey, series VI, vol. 26, p. 91, 1927.

[11] Weller, J. M., Geology and oil possibilities of extreme Southern Illinois: Illinois Geol. Survey Rept. Inv. 71, p. 49, 1940.

[12] Cady, G. H., Coal resources of District V: Illinois Geol. Survey Coop. Mining Series Bull. 19, p. 34, 1919.

[13] English, R. M., and Grogan, R. M., Omaha Pool and Mica-Peridotite Intrusives, Gallatin County, Illinois, in Structure of Typical American Oil Fields, Vol. III, Am. Assoc. Petroleum Geologists, pp. 197–201, April 1948.

in one locality [14] have been found in the district. It is not known whether the granite was derived from a local intrusion or from a remnant of glacial till.

Structural Theories.—There have been two theories proposed to explain the structural history of the district. Both are briefly outlined here in order to give a possible explanation for the first three structural events of the sequence: (1) pre-dike fracturing, (2) basic dike intrusion, and (3) major block faulting.

Weller and Butts [15] suggested that the dome structure was caused by intrusion of a deep seated magma of which the dikes are surface evidence. This intrusion "upwarped the overlying strata" stretching and fracturing them in a radial pattern across the area of the dome. These fractures became normal faults of varying displacements when the dome collapsed due to lateral spreading of the igneous mass, and in part, to contraction while cooling. However, this theory does not satisfactorily explain four very pertinent facts: (1) the similarity in strike of the dikes, (2) the difference in strike of the dikes and the major faults, (3) the distinct time difference between intrusion of the dikes and major block faulting,[16] and (4) the Shawneetown-Rough Creek thrusting.

A more recent theory advanced by J. M. Weller,[17] and concurred with by Sutton,[18] proposes that the initial factor in the formation of the dome was compression from the south or southeast which most likely occurred at the time of the Appalachian folding, domed the strata, released pressure from deep magmatic material, and caused the Shawneetown-Rough Creek thrust and two asymmetrical anticlines west of this fault. Tension fractures developed parallel to the direction of compression (slightly west of north) and it was into these fractures, which could have reached the depth of a deep-seated parent magma, that the dikes were intruded. Release of the compressive forces caused the collapse of the dome and complex normal faulting. It is this writer's opinion, in view of the extensiveness and complexity of the faulting, that the release of pressure was quite sudden, as might be expected to result from the Shawneetown-Rough Creek thrust faulting.

Major Faulting at the Hutson.—The Sandy Creek and Moore Hill fault systems (Fig. 2) are a part of the complex major faulting in the district which can be dated only as post-Pennsylvanian, pre-late Cretaceous. It is obvious that the major faulting is later than the dikes since (1) no dikes have been intruded into any of the principal faults, (2) fluorite veinlets, subsequent to the major faulting, in places penetrate dike rock, and (3) where met by

[14] Weller, J. M., and Grogan, R. M., An occurrence of granite in Pope County, Illinois: Jour. Geology, vol. 53, no. 6, pp. 398–402, November 1945.

[15] Weller, Stuart, and Butts, Charles, The geology of Hardin County: Illinois Geol. Survey Bull. 41, pp. 56–57, 1920.

[16] Although Weller and Butts do not state that the dikes were intruded into the initial fractures caused by upwarping, this would explain the time distinction problem. However, it is not likely that this type of fracture would reach to the depth of a deeply buried parent magma which has not yet been found by drilling.

[17] Weller, J. M., Geology and oil possibilities of extreme Southern Illinois: Illinois Geol. Survey Rept. Inv. 71, pp. 49–51, 1940.

[18] Sutton, A. H., The Western Kentucky fluorspar district, text accompanying Geologic Map of the Western Kentucky fluorspar District: U. S. Geol. Survey Field Studies Map MF-2, 1951.

faults of the major systems the dikes are offset. At coordinate 7945 north on the 200-foot level of the Hutson mine a footwall split off the east fault of the Sandy Creek system has offset the dike six feet to the west (Figs. 3, 7). This same fault can also be seen to offset the east dike on the 300-foot level, but apparently dies out before reaching the 425-foot level since no offset is apparent there.

Calcite-Fluorite-Sulphide Mineralization.—The major mineralization in the district was the deposition of economically important fluorite and associated sulphides in some of the fissures produced by the above mentioned faulting, and the replacement of limestone in some places by these minerals to form the flat-lying bedding replacement deposits. These vein and replacement deposits in the Illinois-Kentucky district have been the source, since 1880, of more than 6,000,000 tons of fluorspar concentrates, representing 87 percent of the United States production and about one-third of the world production.[19]

Concerning the fluorspar deposits in Kentucky, also applicable to the Illinois deposits, Currier [20] considers it "unlikely indeed that the time of deposition of any one mineral was distinctly separated from the others, *except in the case of part of the zinc blende.*" [21] Currier also recognized two stages of sulphide deposition in a discussion of the paragenesis of the minerals in the great vein deposits at Rosiclare, Illinois: "The sulphides of lead, zinc and copper . . . were probably deposited nearly simultaneously after fluorspar, although some initial deposition may have accompanied the formation of the fluorspar, since in many places they are found disseminated through, and entirely surrounded by, the spar." [22]

At the Hutson mine area fluorite and calcite were deposited during this major period of mineralization in footwall splits from the east fault of the Sandy Creek fault system. A drift on the 140-foot level (now inaccessible) follows one of these fluorspar bearing splits which strike north 50 to 55 degrees east, crossing or ending against the Hutson dikes as discussed earlier. Small tonnages of high-grade spar have been mined from at least two of these splits. No sulphides have been reported occurring with the spar and none are present on the old dumps. Calcite with traces of fluorite fills the narrow fissures along these minor fractures on the 200-foot level.

Post-fluorite Faulting.—Evidences of post-fluorite faulting are commonplace in the main vein deposits of the district. The post-fluorite faults were relatively minor movements with a largely horizontal component of movement, as shown by nearly horizontal slickensides on the vein minerals, or between vein minerals and wall rock. Other evidence of post-fluorite faulting includes shear cracks within the vein minerals and development of "center-slips" in places within the veins. A "textbook" example of a definite post-

[19] Sutton, A. H., Fluorspar resources of the southeast, unpublished manuscript, p. 4, 1950.
[20] Currier, L. W., Fluorspar deposits of Kentucky: Kentucky Geol. Survey, series six, vol. 13, p. 59, 1923.
[21] Italics are by this writer.
[22] Currier, L. W., Economic geology section *in* Geology of Hardin County: Illinois Geol. Survey Bull. 41, p. 258, 1920.

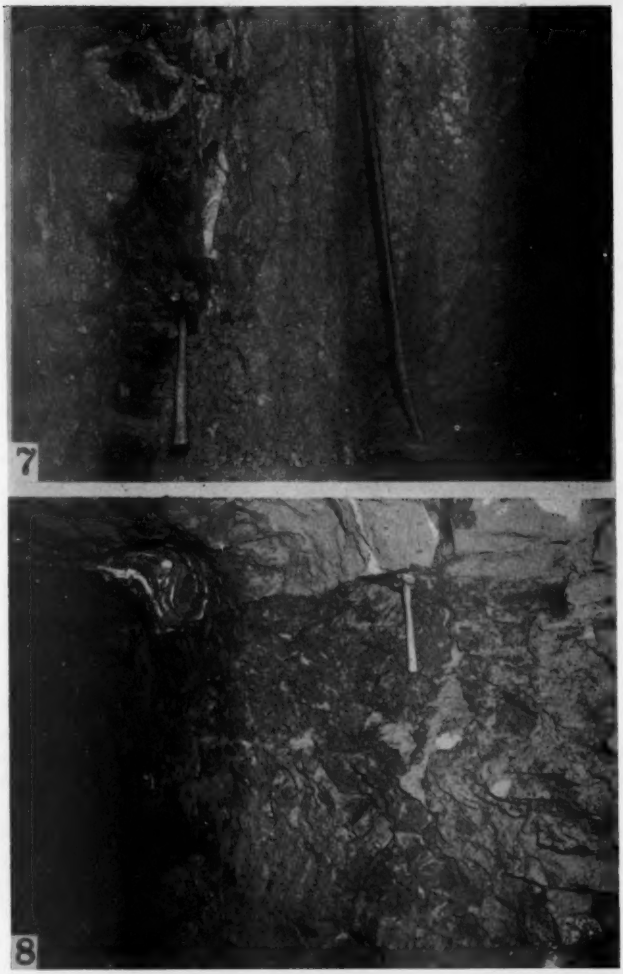

FIG. 7. East dike at coordinate 7945 north on the 200-foot level. View is toward the south. Contact between light green, hydrothermally altered dike and dark gray, jasperoidal St. Louis limestone is marked by hammer and aluminum paint line. The dike is cut-off at calcite vein along a post-dike-pre-zinc fault behind steel pipe.

FIG. 8. Fault along bedding plane "A" cutting west dike in south wall of 300-foot level crosscut from new shaft to vein. Dike is 7 feet wide from largest calcite veinlet on left to black limestone above and to right of hammer. Dike below fault has been shifted 18 feet east (left). Note much shattered limestone below fault.

fluorite fault can be seen on the 700-foot level of Alcoa Mining Company's mine at Rosiclare, Illinois. Here fluorite in the "Blue Diggings" vein has been sharply cut and offset. These post-fluorite faults may have been due to readjustment to differential pressures within the tilted and wedged fault blocks or, more probably, to recurrent Appalachian compression.

Earlier, in a description of the dikes at the Hutson mine, evidence of horizontal movement along the dikes was given. Since the brittle vein minerals are not sheared or brecciated, this movement must have preceded zinc sulphide mineralization and was, moreover, a prerequisite thereto. That the movement was post-fluorite is well shown at coordinate 7945 north on the 200-foot level (Fig. 3). Here the east dike is offset six feet to the west, as described above under "Major Faulting at the Hutson," by a footwall split from the east fault of the major Sandy Creek system. The calcite vein along this split, which was deposited during the major calcite-fluorite-sulphide mineralization in the district, is in turn offset by horizontal movement along the east dike. On the east side of the dike the calcite vein has been displaced three feet to the south. It is reported that some fluorspar was taken from this vein in a stope above the 200-foot level.[23]

Though slight, this movement to the south, coupled with an undetermined amount of shift to the north by the country rock on the west of the west dike, was sufficient to open northeast striking and southeast dipping tension fractures between the dikes.

Late Stage Sphalerite Mineralization.—The post-fluorite faulting along the east dike opened deep channelways along which initially calcite, and then zinc and iron sulphide mineralizers could ascend. The tension fractures described above served as excellent feeders through which the mineralizers penetrated and massively replaced the limestone.

Currier, as previously discussed, recognized a phase of sulphide mineralization that was later than the main calcite-fluorite-sulphide mineralization in the district. He emphasized the late stage sulphide mineralization as contributing the greater part of the sulphides associated with the major vein deposits. He observed sulphides of both lead and zinc deposited largely along "centerslips" developed by post-fluorite movement within the veins, and recognized late sphalerite replacing fluorite.[24] Currier's conclusion that part of the zinc sulphide was deposited at a distinctly different time than the other vein minerals is certainly strengthened by the evidence at the Hutson mine.

Post-late Stage Sphalerite Readjustment.—Following deposition of the late stage sphalerite there were further structural readjustments within the St. Louis fault block in which the ore occurs, as are shown by post-sphalerite movements along nearly horizontal bedding planes at various places in the 200-, 300- and 425-foot levels. In the 200- and 425-foot levels slickensides show the shifting was east-west, nearly perpendicular to the vein and dikes.

[23] Reed, Avery H., Sr., personal communication.

[24] Currier, L. W., Economic geology section *in* Geology of Hardin County: Illinois Geol. Survey Bull. 41, pp. 258–259, 1920.

They are especially prominent in the 425-level, although the displacements here are very small, generally only a very few inches. In the 300-foot level, however, displacements up to 18 feet have been measured. Since no slickensides have been observed on the bedding planes in this level, it can only be presumed that the direction of movement was the same as in the levels above and below.

In the block diagram (Fig. 9) it will be noted that the west dike (Figs. 8, 10) has been offset 18 feet, but the east dike and vein (Fig. 11) only 7 feet by movement along bedding plane "A." Thus, the distance between east and west dikes below bedding plane "A" is only 84 feet or eleven feet less than above plane "A" where they measure 95 feet apart. The answer to this anomaly continues to elude the writer.

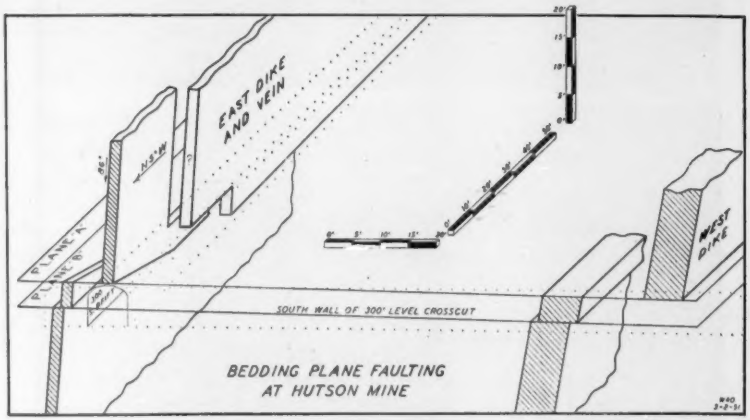

FIG. 9.

Behre [25] gives a six-fold classification of bedding-plane faults. His "transecting accessory" type is the only one of the six that may occur in tension fault areas but is probably more common in areas of thrusting. Bedding-plane faults of the transecting accessory type are so termed "because they are movements accessory to larger faults that transect the bedding." The Hutson bedding-plane faults are undoubtedly of this nature.

Some of the areas where bedding-plane faults of this type have been described are at Leadville, Colorado,[26] Weston Pass, Colorado,[27] and at Good-

[25] Behre, Charles H., Jr., Bedding-plane faults and their economic importance: Am. Inst. Min. & Met. Eng. Trans., vol. 126, pp. 512–529, 1937.

[26] Emmons, S. F., Irving, J. D., and Loughlin, G. F., Geology and ore deposits of the Leadville Mining District, Colorado: U. S. Geol. Survey Prof. Paper 148, pp. 64–65, 189, 190, 1927.

[27] Behre, Charles H., Jr., The Weston Pass Mining District, Lake and Park Counties, Colorado: Colorado Sci. Soc. Proc., pp. 13, 63–65, 67, 1932.

FIG. 10. Closeup view of the east 3 feet of the west dike shown in Figure 8. Note drag and fracturing of the calcite veinlets that fill pre-zinc fractures parallel to the dike.

FIG. 11. Fault along bedding plane "A" in north wall of 300-foot level crosscut from new shaft to vein. Hammer marks approximate west side of east dike and vein below fault. Note gouge immediately above hammer. The dike and vein have been offset 7 feet to the west above fault and are marked by calcite in upper left corner of photo.

spring, Nevada,[28] accessory to thrust faults, and at Philipsburg, Montana,[29] accessory to what appear to be normal faults. Transecting accessory bedding-plane movements are probably present to some degree in most faulted areas, but are not easily recognized unless they can be observed offsetting veins, dikes, or joints. For example, the bedding-plane faults shown in Figure 9 went unrecognized during the driving of the 300-foot level crosscut towards the east until the faulted west dike was encountered. Nothing about the bedding-planes warranted any particular attention since they appeared, in passing, to represent only thin shaly partings between limestone beds of the St. Louis. No slickensides have been observed anywhere on these planes of movement.

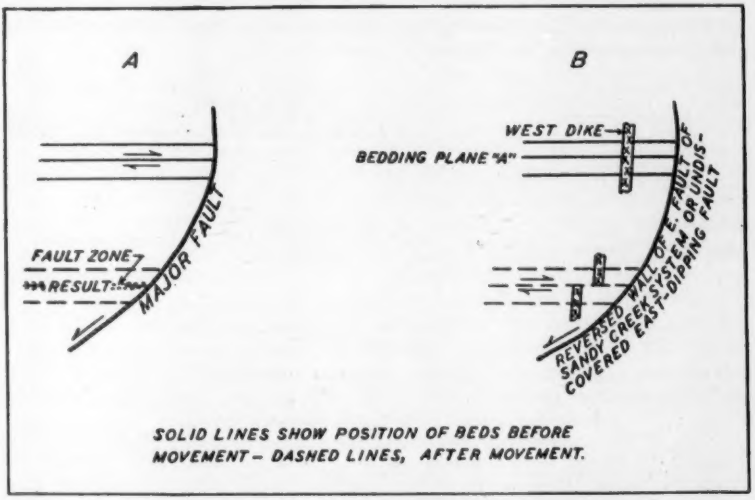
A
B
FAULT ZONE
RESULT
MAJOR FAULT
WEST DIKE
BEDDING PLANE "A"
REVERSED WALL OF E. FAULT OF SANDY CREEK SYSTEM, OR UNDISCOVERED EAST-DIPPING FAULT
SOLID LINES SHOW POSITION OF BEDS BEFORE MOVEMENT – DASHED LINES, AFTER MOVEMENT.

FIG. 12.

Figure 12-A is Behre's diagram showing the mechanics of this type of bedding-plane faulting, and Figure 12-B is the same diagram modified to show the conditions observed and inferred at the Hutson mine. Diagram B indicates the necessity of the normal fault to dip east or southeast. Referring to Figure 2, however, it is noted that the east fault of the Sandy Creek system should dip northwest. Therefore, in order to meet the requirements necessary for the movements as diagrammed, one of two unknown conditions must exist: (1) local reversal of dip of the east fault of the Sandy Creek system

[28] Hewett, D. F., Geology and ore deposits of the Goodsprings Quadrangle, Nevada: U. S. Geol. Survey Prof. Paper 162, Fig. 8, 1931.

[29] Emmons, W. H., and Calkins, F. C., Geology and ore deposits of the Philipsburg Quadrangle, Montana: U. S. Geol. Survey Prof. Paper 78, pp. 183–184, 1913.

to give it a southeast dip at the level of its transection with the bedding-plane faults or (2) a southeast or east dipping fault located between the area of bedding-plane movement and the east fault of the Sandy Creek system. Local reversals of dip have been observed in fluorspar mines in the district. However, where they occur the fault walls are quite steep and it is questionable whether the reverse dip of the wall would be sufficiently flat to cause the differential stresses necessary to development of movements along the bedding.

Since the bedding-plane faulting is definitely post-late sphalerite it would logically follow that at least a few of the faults in the district, possibly including the east fault of the Sandy Creek system, have experienced three phases of movement: (1) post-dike, pre-fluorite, (2) post-fluorite, pre-late sphalerite, and (3) post-late sphalerite. The displacement was primarily vertical during (1), largely horizontal during (2), and probably vertical during (3).

Paragenesis.—The following table summarizes the stages of mineralization and the paragenesis of the Hutson minerals:

Stage	Mineral	Loci of deposition	Economic significance
I	Calcite Quartz Fluorite *Sphalerite *Galena	Along fissures in the footwall faults of the Sandy Creek system	Major in the district but minor at the Hutson mine
II	Calcite Sphalerite Marcasite **Galena Pyrite	In lode-fissure along east dike and replacement of adjacent fractured limestone	Major at the Hutson and at present secondary in the district
III	Calcite Fluorite	In rare, post-sphalerite fractures	None

* Occurs in most of the fluorite deposits of the district but absent at the Hutson.
** Very slight trace present.

For detailed discussions of the paragenesis of the Kentucky fluorspar deposits the reader is referred to Currier,[30] and for the Illinois deposits to Bastin.[31] Since Bastin's report was written nearly ten years before discovery of the sphalerite-rich bedding-replacement deposits in Illinois, his statement that "sphalerite is inconsequential in quantity" [32] in the fluorspar bedded deposits is no longer valid. Also, Bastin observed sphalerite from the Illinois veins which was only contemporaneous with the fluorspar, although he did report galena in post-fluorite fractures in the veins.[33]

The second stage of mineralization shown in the above chart, and with which we are primarily concerned at the Hutson mine, quite evidently was initiated by considerable calcite deposition. Ragged patches of coarse calcite, as previously discussed, are present in many places along the lode-fissure.

[30] Currier, L. W., Fluorspar deposits of Kentucky: Kentucky Geol. Survey, ser. b, vol. 13, pp. 59–71, 1923.
[31] Bastin, E. S., The fluorspar deposits of Hardin and Pope Counties, Illinois: Illinois Geol. Survey Bull. 58, 1931.
[32] Idem, p. 57.
[33] Idem, pp. 26–27.

Where calcite is in contact with sphalerite the crystal faces of the former are destroyed by replacement sphalerite.

If the very pure sphalerite band in the center of the lode-fissure is interpreted as being a true fissure filling that was formed after the replacement of adjacent limestone by alternation of sphalerite and marcasite, then it can be concluded that part of the sphalerite was deposited later than the marcasite.

Pyrite is scarce but occurs as tiny cubes within the highly altered limestone and dike rock, and as pyritohedrons and cubes lining minute cavities in the marcasite, indicating later formation than at least part of the latter.

Temperature of Ore Emplacement.—Behre [34] classes the fluorite deposits of western Kentucky as epithermal and recent studies of two-phase inclusions in minerals by Smith [35] and by Grogan [36] indicate a low temperature of deposition for several minerals from the Illinois-Kentucky district.

Determinations of temperature of deposition of a given mineral using the two-phase (liquid-gas) inclusions in the mineral are based on the assumption that the inclusions were one-phase (liquid) at the time of formation, and that due to contraction during cooling a gas bubble formed in the liquid. It must also be assumed, as pointed out by Kennedy,[37] that no material has been added to or lost from the inclusions since their formation. When the mineral is heated the temperature at which the gas bubble disappears is assumed to be the temperature of deposition of the mineral after a correction for the estimated pressure during mineralization is applied. The temperature of disappearance of the gas phase is determined visually with a microscope equipped with a heated substage, or indirectly by decrepitation of the mineral.

Grogan, by the visual method, found the temperature of disappearance of gas bubbles in "primary" inclusions (parallel to the crystal faces) in four fluorite crystals to range from 83° to 113° C and from 139° to 167° C in a fifth crystal. "Subsequent" inclusions (parallel to cleavage planes) gave temperatures ranging from 112° to 172° C in six crystals. He estimates that correction for pressure would increase these temperatures by 9° to 14° C.

Smith,[38] using the decrepitation method described by Scott,[39] studied a sample of sphalerite from the Hutson mine. He found three decrepitation inflections: 107° ± 10° C due to filling of fluid inclusions, 136° ± 10° C fairly certainly due to misfit of solid inclusions, and 300° to 400° C due to an unknown cause. Smith reported that he successfully checked the 107° beginning of decrepitation visually.

[34] Behre, Charles H., Jr., Problems of the genesis of mineral deposits of the Southeastern States, Symposium on Mineral Resources of the Southeastern United States, 1949 Proceedings, Univ. of Tenn. Press, p. 32.

[35] Smith, F. Gordon, Laboratory testing of "pneumatolytic" deposits: ECON. GEOL., vol. 44, pp. 624–625, 1949.

[36] Grogan, R. M., Formation temperatures of Southern Illinois bedded fluorite as determined from fluid inclusions, presented before Geological Society of America, Washington, D. C., Nov. 1950 .

[37] Kennedy, George C., "Pneumatolysis" and the liquid inclusion method: ECON. GEOL., vol. 45, pp. 533–547, 1950.

[38] Smith, F. Gordon, personal communication.

[39] Scott, H. S., The decrepitation method applied to minerals with fluid inclusions: ECON. GEOL., vol. 43, pp. 637–654, 1948.

The writer has not made a study of temperature of ore deposition, but it appears to him that the Hutson ore body manifests so many characteristics of *mesothermal* deposits that have been described by highly qualified students of geologic thermometry that its classification as a mesothermal ore body warrants consideration. Bateman,[40] under the heading of "intermediate temperature" lists the following characteristics which are typical of the Hutson deposit: "extensive wholesale replacement of rocks. . . . Fine- to medium-grained textures prevail." Grout [41] gives a list of criteria suggesting "Hydrothermal alteration at moderate depth (mesothermal)" among which the following have been observed at the Hutson and reported in this paper: "leucoxene from ilmenite, . . . chlorite from mica. . . . Textures: . . . banded . . . drusy cavities. . . . Presence of . . . chlorite, calcite, . . . fibrous biotite, leucoxene . . . basic rocks turning dull green. . . . All mafic minerals altered if attack is moderate."

If the Hutson ore deposit is mesothermal, either the temperature of the late-stage sphalerite mineralization was higher than that of the main calcite-fluorite-sulphide mineralization in the district, or the latter mineralization was at a higher temperature than generally has been supposed (epithermal).

ACKNOWLEDGMENTS.

Dr. A. H. Sutton, Geologist of the Fluorspar Division of Alcoa Mining Company, with whom the writer has had the privilege of working in the fluorspar district for the past four years, provided valuable criticism and essential ideas for this paper. Several very interesting and helpful conferences regarding the Hutson dikes were held with Dr. Robert M. Grogan, at that time with the Illinois State Geological Survey and now with the DuPont Corporation.

The writer is grateful to the Aluminum Company of America for the opportunity and privilege to make this study, and to the engineering staff of the Rosiclare office of Alcoa Mining Company for furnishing surveys and mine data.

ALCOA MINING COMPANY,
ROSICLARE, ILLINOIS,
Oct. 18, 1951.

[40] Bateman, Alan M., Economic Mineral Deposits, John Wiley & Sons, Inc., New York, p. 100, 1942.

[41] Grout, Frank F., Petrography and Petrology, McGraw-Hill, New York, p. 426, 1932.

KARST ORE IN YUNNAN.

FRED SEARLS, JR.

THE political situation in southwestern China is such, that further useful scientific contributions to the knowledge of its areal and economic geology are unlikely for some years to come. Perhaps this will serve as a valid excuse for publication now of the following explanation of certain unusual lead-silver occurrences near the China-Burma border, written as a portion of a report to the Yunnan-Ming Hsing Mining Company in 1921. The writer visited the region in 1920, as an employee of Newmont Mining Corporation—one of the former company's American shareholders; and although forced to leave the most interesting area by hostile activities (Fig. 1) of the indigenous population and defection of his own "army," established to his own satisfaction, the derivation and manner of accumulation of these deposits that have given rise to an aggregate of several hundred thousand tons of lead slag formed in the primitive smelting activities in these regions.

The area involved is between the Mekong and Salween Rivers, between 98° and 100° longitude east of Greenwich and between 22° and 24° north latitude, comprising in part an area of dispute between the Chinese and Burmese governments since 1898. As of 1920, this area had never been fully traversed by any white people and was in part in control of the Was or Kawas, as they were called by the Chinese. The index map, Figure 2 shows the location. The principal mining has been at Munai (or Monai) and in the vicinity of Ta Tong Chuan, north of Teng Yueh.

FIG. 1. Ultimatum received by the party from the Kawas. Red pepper and piece of charcoal, wrapped up in a leaf and tied to the notched stick with a bark string. Pepper—emblem of anger and hostility; charcoal—death and destruction; bird feathers—quick action. Each notch in the stick is supposed to represent one village, from which warriors would be drawn. Bearers of the message gave names of villages represented by some of the larger notches.

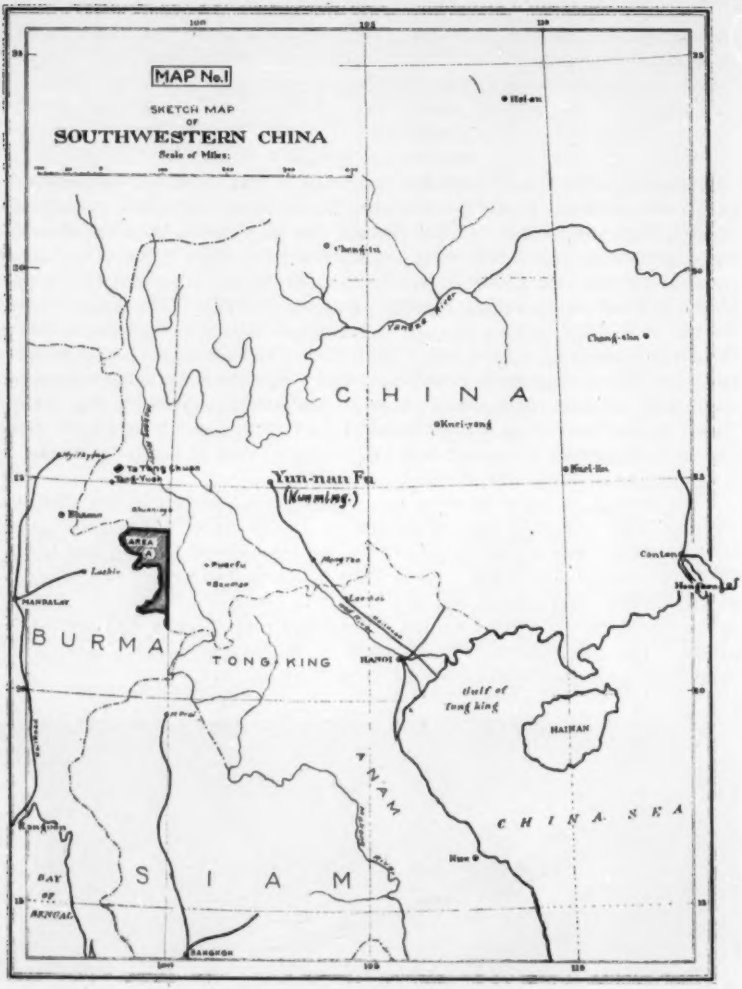

FIG. 2. Index map.

"SINK HOLE" ALLUVIAL DEPOSITS IN LIMESTONE AREAS.

The ore deposits at Mu Nai, and probably most or all of the mines in the Wa States, are in limestone. So also are the deposits at Ta Tong Chuan and, with one exception, the other known occurrences in the Ming Kwan area. The writer has gradually become apprised of the fact that the presence of

old Chinese workings and even of fairly extensive slag piles, in one of these limestone areas, does not necessarily point to the existence, or even the former existence, of a silver-lead orebody of any of the types heretofore recognized, or that is commercial from a foreign point of view. A very considerable portion of the ore that has been produced, has come from curious superficial placer-like deposits which no one but Chinese could have worked.

These deposits are so extraordinary and their method of accumulation so unusual, that the writer considers it advisable to record a brief discussion of them. A proper comprehension of the process by which they are formed, and of their importance, at an earlier stage of the Company's operations might have saved considerable expenditures.

The limestone beds in which the orebodies occur are over one thousand feet thick. Commonly, they are underlain by argillaceous rocks; shale or slate at Ta Tong; tuffaceous shale at Mu Nai; and shales elsewhere. The entire region is extremely mountainous. In the mountain-making movements, these brittle limestones overlying less competent beds have been faulted and broken into blocks. In the areas here under consideration, the faulting is normal.

When a mountain range, of which the more elevated portion consists of such thick limestones faulted into blocks becomes exposed to erosion, the situation is somewhat analagous to a pile of concrete blocks on a slate roof. When it rains the run-off is on the slate. The important differences are that, in actual cases, the blocks are very large and are also quite soluble in water. The rain falling on any given block, the surface of which is of course uneven, runs toward and into the nearest bounding crack. More water traverses the surface of the block near the crack. In consequence the edge of the crack dissolves more rapidly than the rest of the block, and a solution hole, or a line of holes, begins to form near the crack. In the actual case the cracks are faults, commonly of large displacement and thousands of feet long; the blocks contain many millions of tons; and the solution holes reach to an area of several square miles. Once the solution hole starts to form, there can be no transportation of material of any kind away from the area draining into the depression, except by the water that runs down the crack. The larger the depression becomes, the more water drains into it; the more water draining into it, the faster it grows. In this way what may be termed sink-hole topography is initiated.

As these solution holes or sinks grow deeper they also grow larger, by recession of their sides from the fissure. Where the fissure draining the sink has a flat dip, there appears to be a tendency for the side of the sink which it undercuts to remain vertical or very steep. The other sides have, characteristically, a concave slope in their lower parts. As the sides recede and the slopes grow longer, the erosional process *on the slopes* ceases to be one of simple solution, and becomes the ordinary atmospheric erosion of a limestone slope where solution is aided by corrasion and the transporting power of rain water. Gulches and canyons are formed and the upper slopes become convex. But the material transported can go no farther than the sink. The bigger and

deeper the sink, the bigger the area around and above it where erosion is normal.

The result of this method of erosion is the progressive accumulation of the less soluble impurities formerly distributed through the limestone into a much smaller volume in the bottom and sides of the sink hole. They weather out as drift melts out of a glacier, or as the flint nodules accumulate in the soil of chalk areas. Depending on the relative solubility, the drainage area of the

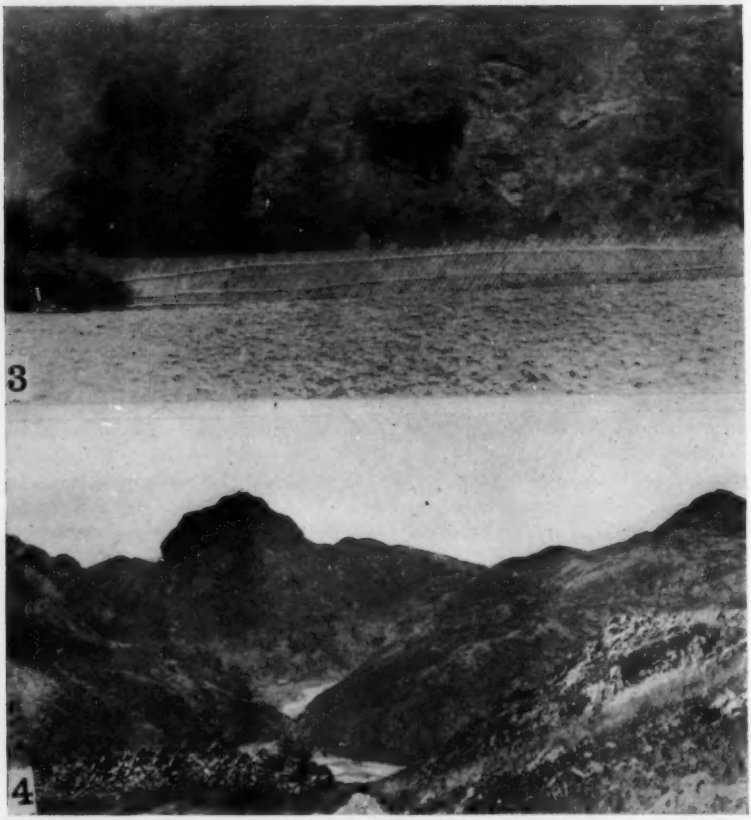

FIG. 3. (Upper.) Former drainage vent of Bei Yun Shan sink near Ta Tong. Sink has now reached horizon shown in foreground and drains into another lower hole on same fissure.

FIG. 4. (Lower.) The Mu Nai Sink looking north. The east side of this sink in the distance is cut in shale and sandstone but drainage is by subterranean channels through the limestone.

FIG.. 5. Process by which sinks deepen, slumping down of alluvium as bedrock bottom of sink dissolves. Scarp on hill shows previous slump.

sink, and the proportion of impurities in the limestone, the degree of concentration of the less soluble constituents may vary widely. It may easily exceed a ratio of one hundred to one.

The climate in these regions is one of remarkably even temperature and abundant but not torrential precipitation. Frost and snow are practically absent. Such conditions are probably essential to the evolutions of this type of topography, for two of the most active agents of mechanical erosion—frost and cloudbursts—are lacking. Also it appears that under these conditions, the sulfide of lead is peculiarly stable. Float galena is found all through the area. The oxidized ores of lead—cerussite and anglesite—derived from the outcrop of an orebody are probably, under ordinary conditions, destroyed by mechanical action. They are friable and easily broken up by being rolled down a slope or in a creek. Under the peculiar conditions here obtaining, they also are, therefore, unusually stable.

If it is assumed that a given area and thickness—say a half mile square, five hundred feet thick, containing originally a certain tonnage of sulfide ores in scattered bodies, large or small, rich or lean, veins, seams, small bedded deposits or even larger replacements—the oxidation products of these ores will remain in the residual detritus when this block has been dissolved. And the relative abundance of these sulfides, or oxides and carbonates may have been increased a hundredfold in the process.

But the distribution of the metallic sulfides or of their oxidation products will not be uniform in the accumulated sink hole alluvium. This is an observed fact, and the reason for it is undoubtedly the difference in specific gravity. As noted before, the degradation by pure solution only occurs in the bottom of the sink hole. Soil and detritus move down the upper slopes as under the ordinary process of erosion. This movement is spasmodic. More

work is done during an exceptionally heavy rain than during the entire remainder of the year—or decade. But it is essentially a sluicing action, coupled with a certain amount of settling, well calculated to permit the heavier constituents to settle on bedrock. The settling action is referable to two causes. The material moving down the upper slopes is only partially the insoluble residues. Partly it consists of limestone fragments in process of solution. These fragments continue to dissolve as they move down and after they reach the sink. Also bedrock of the lower slopes and bottoms of the sinks is constantly being dissolved. The combination of these two processes causes a contraction in volume of the alluvium and a lowering of the bedrock. This causes a settling which is, no doubt, gradual in part, but which in part occurs by great slumps or cave-ins of the alluvium. In a few places these extend to the surface like a caved stope. Figure 5 shows such a slump or cave-in in the very bottom of a large sink, and also the scarp or scar of an anterior similar larger occurrence. These are common and represent doubtless the normal process by which these sinks grow deeper.

ORE CONCENTRATION AND OCCURRENCE.

There is little doubt that the combination of these processes permits a concentration of the sulfide and gossan fragments on bedrock. The writer has been in perhaps a hundred Chinese workings sunk in the sink-hole alluvium—and has seen five hundred. These workings disclose a certain amount of gossan ore all through the material, but this amount increases toward bedrock, and in many instances there is a layer consisting of little else than gossan or sulfide fragments from one to ten feet thick lying immediately upon a white marble bedrock. Also, this layer is unevenly distributed. As noted above, the upper slopes of the basin are convex and the lower slopes concave. Though modified by the eccentricities of the resultant topography, there is probably a theoretical contour on this concave curve where material of a given size and specific gravity tends to come to rest under the conditions of an average heavy rain. In certain instances also relative abundance is a function of the position of sources of the float.

One further influence that needs consideration is the action of one sink hole on another. Two or more often start on the same fault; or two on different faults may occur close together. Obviously they will overlap in places; as they become deeper, they become wider and the widening is not of course symmetrical, but goes on by the formation and cutting back of little gulches or canyons. A big sink grows faster than a smaller one and the greater the disparity in size, the more is this true. When a gulch or canyon cutting back from a big sink begins to invade the catchment area of a smaller one, the difference in rate of growth is still more accentuated. The result is that the deeper sink ultimately performs an act of piracy on the smaller one in a manner analagous to the piracy of ordinary stream evolution. Once the gulch performing the piracy cuts clear through the rim of the smaller basin, the alluvium of the latter will begin to pour into the larger basin. The smaller one may be quickly eradicated or may leave a "bench deposit" in sheltered

portions of its area like the benches of a river left stranded hundreds of feet above its present bed. This action may be repeated a half dozen times or more, one sink draining another, until finally, in a mature stage in the life of the range, the real canyons, cutting back from the interrange rivers, invade the larger sinks and terminate this portion of the cycle.

The importance of this process in the present problem is that:

1. In this area considerable bodies of gossan float do not necessarily signal the proximity of a large orebody or vein.

FIG. 6. Cave gulch sink. Upper sink being drained into lower one.

2. Since much of the ore won by the Chinese has come from these alluvial accumulations, the presence of large slag dumps does not necessarily indicate a large body of ore in place. The writer thinks that nearly half of the slag at Ta Tong has come from such "placers." In the whole Ming Kwan area, it is probably a higher fraction. At Mu Nai, it may easily be more than half. Except for the Si Ni Chan mines, the writer saw no important slag pile that was not in a "sink hole."

It will be noted that this method of accumulation does not preclude the existence of large bodies of ore in place. Such deposits could accumulate from

FIG. 7. "Sinkhole" or "Karst" topography.

the float of one large orebody, or a hundred small ones. But certainly a comprehension of these deposits detracts materially from the economic importance to be attached to the slag heaps in this region, or the gossan exposures at Ta Tong.

In recognizing this process of erosion and accumulation of detrital ores, the writer thought, while on the ground, that he had arrived at something not previously described in geologic literature. On pursuing the subject, however, he finds that a similar result, the "Karst Topography," has been described as occurring in Dalmatia, and that an analagous process has been invoked to explain the origin of certain ore occurrences on top of the Pennsylvania limestone in the Joplin district.[1, 2]

14 WALL ST.,
NEW YORK CITY,
Dec. 22, 1951.

[1] U. S. Geol. Survey Bull. 606, 1915.
[2] Except for the first page, this article was part of a report written in 1921.

DISCUSSIONS

ALPINE LEAD–ZINC ORES OF EUROPE.

Sir: A paper by H. L. Jicha, Jr., published in this journal (Vol. 46, No. 7, pp. 707–730, 1951) contains some geological and mineralogical data on the Alpine lead-zinc deposits of Europe. In addition, the paper contains a chemical argument which reaches the conclusion that (1) the deposits were formed by aqueous solutions, (2) the temperatures of the solutions were relatively low, and below 300° C, and (3) the solutions had a pH less than 7. It is my contention that not only were these conclusions not indicated by the recorded data, but that no critical data on composition, density, and temperature of the solutions were given at all. In addition, a number of positive statements beg denial.

Fluid inclusions in hydrothermal minerals are our only direct samples of hydrothermal solutions, and in all discussions of the chemistry of mineral deposition, the composition and density of the inclusions are of first importance. Jicha mentioned the word "inclusions" only once (quoting the excellent work of Newhouse [1]), but he did not report any data on the inclusions in the minerals described.

Jicha stated categorically that two of the deposits are of epithermal type and one is either of mesothermal or of epithermal type. He mentioned a temperature of 300° C, below which the mineralization took place. No determinations of temperature or pressure of deposition were made, and possible thermometric methods were neither employed nor discussed. In the opinion of the writer, such speculations, even though they may appear to be not unreasonable, perform only a negative function of beclouding the real data.

The author's treatment of pH and acidity is too rudimentary for the results expressed. He should have explained why he used the notation: OH_3^+ less than 10^{-7}, solution is alkaline. The usual convention is: H^+ less than 10^{-7}. Any data the author has that hydrogen ions are solvated in this way at the temperatures postulated should be shared with others. Also, neutrality at pH = 7, i.e. $H^+ = 10^{-7}$, is only true at one temperature near room temperature. For example, at approximately 100°, neutrality (i.e. equality of concentration of $H^+ = OH^-$) is when $H^+ = 10^{-6}$, and the ionization product increases approximately 8 percent per degree rise in temperature.[2] In other words, neutrality is at pH values less than 7 at temperatures above room temperature.

[1] Newhouse, W. H., The composition of vein solutions as shown by liquid inclusions in minerals: Econ. Geol., vol. 27, pp. 419–436, 1932.

[2] Kolthoff, I. M., and Sandell, E. B., Textbook of quantitative inorganic analysis: Macmillan, New York, 1936.

Jicha used data of Allen and Crenshaw to prove that wurtzite is only stable in acid solutions. This is in error, since no one has found that wurtzite is stable at all at the low temperatures under discussion. It can be crystallized in acid solutions, but there are no data known to the writer indicating whether it is metastable or sluggishly unstable. In addition, the figure derived from the data shows that wurtzite can be crystallized in alkaline solutions below 250° C. Jicha quoted some conclusions in a paper by the writer [3] but the fact that wurtzite was crystallized in strongly alkaline solutions of NaHS was deliberately withheld. Too little is known about nucleation of metastable crystal forms to make positive statements regarding natural events.

The argument that, because sulphate minerals are deposited by hydrothermal solutions, they must have been acid, has been countered repeatedly in the past. Jicha did not present any data on the concentration of alkaline and alkaline earth ions in the responsible solutions, so there is no way of calculating the acidity or alkalinity.

Sodium sulphide solutions are not unstable when the pH is below 7, as stated by Jicha. Aqueous solutions containing sodium ions and sulphide ions are as stable as almost all solutions of electrolytes. The sulphide ion concentration is sensitive to pH, but the solutions do not disintegrate when acidified.

Deposition of sulphur along with metallic sulphides was said to be a characteristic of alkaline sulphide solutions. Possibly Jicha is confusing these with sodium polysulphide solutions, which may deposit and dissolve sulphur, but this equilibrium is not related to the stability of thio-ions of the metals.

The author has lost sight of some important anomalies of solubility in his eagerness to reiterate his speculation. The following statement is made. "It seems improbable that alkaline solutions could cause any significant solution of limestone or even enough to allow replacement." No data were quoted in support of this postulated probability. Barite, a mineral with known low solubility in water, not greatly affected by pH, was deposited in each of the vein types described. Since both barite and calcite were deposited in the same deposits, and, as a first approximation, in similar order of magnitude, one would expect somewhat similar solubilities of these two minerals in the solution. Using data given by Koltoff and Sandell [2] (pp. 38, 55), it can be calculated that in acid solutions calcite is very much more soluble than barite, that this is reversed in alkaline solutions, and that they reach comparable solubility at a pH between 7 and 8 at room temperature. No quantitative meaning can be taken from such calculations, since solubility and ionization products of the solutes and water change with temperature and pressure, and in addition there are a number of compositional variables not considered. One can speculate that there is a probability that quantitative values, when determined, will show that the solutions could have been neither strongly acid nor strongly alkaline, but to state that alkaline solutions cannot dissolve limestone is erroneous.

One criterion which could be used is whether or not the fluid inclusions contain CO_2 under pressure. If acid hydrothermal solutions became neu-

[3] Smith, F. G., Solution and precipitation of lead and zinc sulphides in sodium sulphide solutions: ECON. GEOL., vol. 35, pp. 646–658, 1940.

tralized by reaction with limestone, as postulated by Jicha, then the CO_2 content in the solutions would have increased to some limit (either the neutralization would have been completed before the solutions were saturated with CO_2, or afterward). Therefore, little or no free CO_2 in the fluid inclusions of the vein minerals would indicate alkaline rather than acid solutions. If the minerals are degassed under vacuum, and then crushed under a viscous liquid, presence of compressed gases in inclusions is indicated by sudden appearance of bubbles. There is good evidence that minerals as soft as anhydrite, calcite, and gypsum can retain CO_2 under very high pressure;[4, 5] therefore, it is probable that sphalerite could retain CO_2, at least in small inclusions.

I wish to make it clear, in case this note provokes further discussion, that I have no convictions regarding the conditions under which the lead-zinc ores being discussed were deposited. They may have been in fact deposited by acid hydrothermal solutions under 300° C as postulated, but Jicha has not attempted to gather the data by which the postulate could be tested.

F. GORDON SMITH.

DEPARTMENT OF GEOLOGICAL SCIENCES,
UNIVERSITY OF TORONTO,
TORONTO, CANADA,
Dec. 3, 1951.

LATE MAGMATIC ORES AND THE PALISADE DIABASE SHEET.

Sir: In his interesting contribution on late magmatic oxide ores C. H. White [1] makes reference to the Palisade diabase sheet. This is the only example quoted by him of which I have first-hand knowledge, but there seems to have been some misinterpretation and neglect of the available evidence in this case which call for comment.

The crux of the matter is in the following two sentences. "The Palisades of the Hudson River is a horizontal sill of basic igneous rock nearly 1,000 feet thick with an olivine rich zone near the base, 'above which lies a zone richer in basic pyroxenes,' while in the upper third of the section 'titaniferous iron ore is sufficiently abundant to be a major constituent.' *That is, the lighter magma came in first, followed by the intermediate and finally by the heaviest, the order in which, according to the abyssal theory, they would have been released.*"

The first sentence quoted is a correct statement with two qualifications: (1) the maximum enrichment in pyroxene is in places below the olivine-rich zone; (2) iron ore, though a major constituent in the upper part of the sill, does not exceed 6 percent by volume.[2]

[4] Spezia, G., Sulle inclusioni di anidride carbonica liquida nella anidrite associata al quarzo trovata nella galleria del Sempione: Atti Accad. sci. Torino, vol. 39, pp. 521–532, 1904; Sulle inclusioni di anidride carbonica liquida nella calcite di Traversella: Atti Accad. sci. Torino, vol. 42, pp. 261–269, 1907.

[5] Kinoshita, K., Gypsum crystals from Ishigamori: Japanese Jour. Geology and Geography, vol. 3, pp. 113–118, 1924.

[1] The formation of late magmatic oxide ores: ECON. GEOL., vol. 46, no. 7, pp. 779–781, 1951.

[2] Walker, F., Differentiation of the Palisade diabase, New Jersey: Geol. Soc. America Bull., vol. 51, no. 7, Table 1, pp. 1059–1105, July, 1940.

The second sentence (italicized by F. W.) is, however, a complete non-sequitur. There is no evidence in the previous sentence, nor anywhere else, that the Palisade diabase was emplaced by more than one magmatic impulse, apart from a very minor and localized injection of later undifferentiated basaltic material at Weehawken [3] and a minute proportion of aplite in the upper and lower chilled phases (p. 1065). The sheet shows, on the contrary, every in-

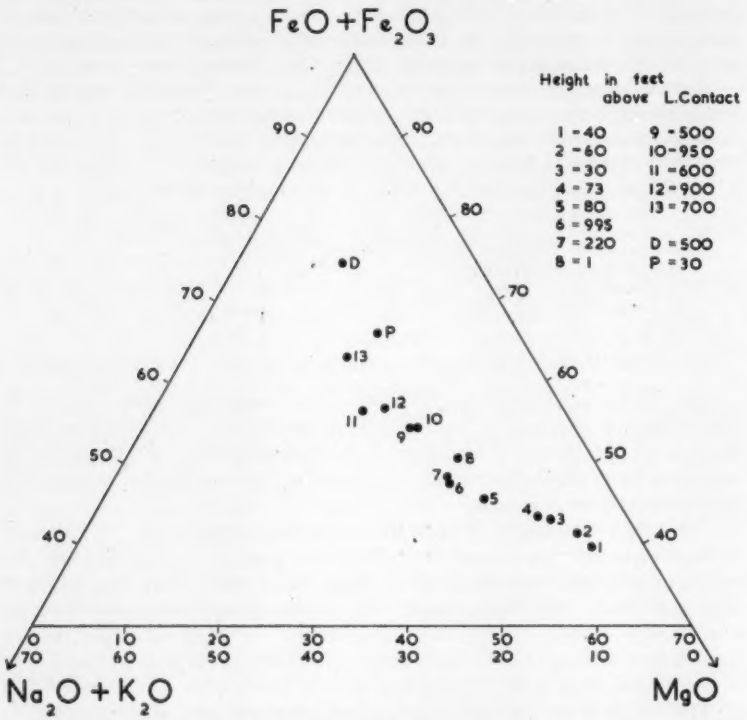

FIG. 1. 1–13 represent diabase from the George Washington Bridge section of the Palisade sill. P and D are cross cutting diabase-pegmatites from the same section and from the Delaware River, respectively.

dication of differentiation in place, first by settling of early olivine crystals to join a well defined layer above the lower chilled phase, second by settling of pyroxene crystals extending much longer and brought gradually to a halt by increasing viscosity and by crystal interference, and third by an upward infiltration of rest-magma accompanying the settling process. The quantitative evi-

[3] Walker, loc. cit., pp. 1086–1087.

dence on which these conclusions are based is given in Tables 1, 3, and 5 of the article cited. Apart from the insignificant amounts of basalt and aplite in the chilled phase there are no true intrusive contacts within the sheet.

The differentiation process involved gradual iron-enrichment of the rest-magma up to a fairly late stage, but in neither the normal rock nor in its pegmatitic inclusions does iron ore exceed 10 percent by volume.

Two new analyses of contemporaneous, but cross-cutting veins of diabase-pegmatite from the George Washington Bridge section, and from the southern extension of the sheet to the Delaware River, show the further stage of iron enrichment, but even here the total percentage of ($FEO + Fe_2O_3 + TiO_2$) does not exceed 25. In no case is there any accumulation of the stratiform bands of relatively pure oxide ore which characterize the great layered complexes. The continuous nature of the variation is shown in the triangular diagram of Figure 1 with MgO, ($FeO + Fe_2O_3$) and ($Na_2O + K_2O$) as co-ordinates. Chemical analyses from the complete George Washington Bridge section [4] are plotted plus those of the two cross-cutting diabase-pegmatites (marked P and D), which show the greatest amount of iron enrichment.

To pass from what seems established with reasonable certainty to more speculative matters, it is suggested that the cross-cutting diabase-pegmatites, which have a well-marked hydatogenic mineralogy, represent the outward passage of thin residual fluids enriched in iron. These, if they penetrated the chilled phases of the sheet, would be capable of metasomatizing contact limestones to become fixed as iron ores of the Cornwall type. There are no such contact limestones in the Newark Series, but the association of the iron ores of Pennsylvania with the contacts of diabase sheets (co-magmatic with the Palisade intrusion and cut by similar diabase-pegmatites) with Paleozoic limestones is highly significant and has its own abundant literature.

FREDERICK WALKER.

DEPARTMENT OF GEOLOGY,
UNIVERSITY OF CAPE TOWN,
SOUTH AFRICA,
February 26, 1952.

[4] Walker, loc. cit., Table 3.

REVIEWS

Applied Geology, a Symposium. Compiled and edited by F. M. VAN TUYL AND TRUMAN H. KUHN. Pp. 343; ill. Colorado School of Mines Quart., vol. 45, no. 1-B, Jan., 1950. Price, $3.00.

In 1949, the seventy-fifth anniversary of the founding of the Colorado School of Mines was made the occasion for a three-day gathering of mining and petroleum people at Golden in a series of conferences having the theme, "Mineral Resources in World Affairs." One of the conferences, held as a symposium, produced a notable series of papers and attendant discussion on the general subject of "Applied Geology," and the papers and discussion were subsequently published as number 1-B, Applied Geology, of volume 45 of the Quarterly of the Colorado School of Mines, Golden, Colo., Jan., 1950, compiled and edited by F. M. Van Tuyl and Truman H. Kuhn.

"Applied Geology" is in a way a sampling of the fields of endeavor in which geologists are engaged, and an opportunity is presented for geologists to justify their contributions to the techniques of the utilization of natural resources in some relatively unknown fields. The role of geology in such seldom discussed fields as soil conservation, irrigation engineering, and highway engineering each elicits a paper and discussion. A paper by R. D. Dirmeyer, Jr., on Geology and Irrigation Engineering gives a concise outline of the work of the engineering geologist. The discussion focuses briefly on the question whether the engineering geologist on a dam-building job works "for" the engineer or works "with" him. Geologists have at times been known to become quite wrought-up over this distinction. The student contemplating engineering geology as a career can profit from this discussion; if he is temperamentally loath to work "for" an engineer, he'd better choose another career, because most engineering jobs can have only one boss, who is in most instances an engineer.

The method of approach to each particular subject is, of course, wholly individual with each author. Thus C. E. Dobbin gives us a concise and abbreviated résumé of the main features of the petroleum geology of Colorado, whereas G. F. Kaufmann takes us to the Dutch East Indies to illustrate modern methods in petroleum geology. A. N. Sayre summarizes the status of the application of geology to the investigation of water resources in the United States and especially in the western states.

To the majority of economic geologists, however, the important contribution of this symposium and volume is the series of papers and discussion on wall-rock alteration and its application to ore search. When geologists of the caliber of Butler, Kerr, Lovering, Sales, Schmitt, and Schwartz (not to mention those participating in the discussions) choose sides on this currently most interesting question of wall-rock alteration and, so to speak, throw brickbats at each other, the result makes interesting reading. To be sure, as several speakers pointed out, there are many important areas of fairly complete agreement (some of which seem to be well-established steps from the theory of a generation ago in the direction of a better theory); but there are still areas of point-blank disagreement, the most

notable being the question of mechanism. Shall we use a two-way mechanism of ionic diffusion in a stagnant environment, or transportation in a moving medium? Do the proponents of ionic diffusion really mean that? They seem to talk in terms of radicals and molecules. It looks as if each of us who has pertinent data and ideas on this question of the nature and the mechanism of the process of wall-rock alteration should get them in order, because from these contributions—the previous papers, those of this symposium, and those that will surely follow—we may take another step in the direction of a sound theory on the nature and origin of the ore-forming fluids.

Economic geologists in general owe a vote of thanks to Professors Van Tuyl and Kuhn for their work in compiling the "Applied Geology" volume and to their associates for the work of arranging the conferences.

JAMES A. NOBLE.

CALIFORNIA INSTITUTE OF TECHNOLOGY,
PASADENA, CALIFORNIA,
Feb. 1, 1952.

Giants of Geology. By CARROLL L. FENTON AND MILDRED A. FENTON. Pp. 333. Doubleday & Co., Inc., New York, 1952. Price, $3.50.

Through the writings of Paul de Kruif the layman has been introduced to the evolution of medical science. The Fentons, similarly, have endeavored to trace the history of geology by a portrayal of the pioneers and leaders in this field. They present geologic principles through the mouths of their heroes or during discussions of their heroes' work and achievements.

The book tells of the early Greeks who treated geology as a philosophy rather than a science and who had already advocated geomorphic cycles and hydrothermal theories of ore genesis. The authors critically examine the theories of the ancients and discuss their limitations.

The early "modern" geologists lived at a time when physics, chemistry, and biology were already well established. Guettard, Malesherbes, and Desmarest are vividly pictured as they climb volcano after volcano; Werner comes to life as a vigorous and forceful personality. Hutton, described as the "impious Scott" by his adversaries, is shown rejoicing as he beholds granite cutting sediments along the banks of the river Tilt. Werner, Hutton, William Smith, Lyell, Murchison, Sedgwick, and Agassiz appear on the scene and take their bow, leaving the reader impressed by their work and achievements. Amid descriptions of the lives and struggles of these men neptunists and volcanists wrestle for preeminence, the great Cambrian controversy is fought, processes which change the earth at present and have done so in the past are established, and the existence of an ice-age is proven. As the new science makes its entrance into the New World the pioneers of the west come to life headed by Owen and followed by King, Powell, and Hayden. James Hall, punching noses of his servants, and emphasizing arguments with his finger on the trigger of his shotgun, takes charge of invertebrate paleontology throughout North America. The lives and discoveries of Silliman, Dana, Chamberlin and others, thirty-nine in all, become experience as the reader paces through the pages.

There is wit in the Fentons' writings as they tell anecdotes and experiences of the great ones. Sir William Logan, founder of Canadian geology, returned from the field in frontierman's garb. A merchant in Montreal took pity on him, selling him a pair of boots at half their value. A well-known official soon hurried to the

store and asked for the $5 boots. "$5 boots? Certainly—a pair of those good ones which Sir William Logan bought less than an hour ago!"

The authors place overdue emphasis on nineteenth-century geologists, choosing none of the more recent outstanding proponents of the science. In a book of this type it is difficult to decide on whom to include and whom to omit; however, the founders of modern petrology and economic geology, respectively Harry Rosenbusch and Waldemar Lindgren, were omitted whereas much space was devoted to Mitchell, Eaton, and Miller. Steno is credited with discovering that fossils were living creatures which inhabited ancient seas while his work in crystallography, the famous "Steno's experiment," was not mentioned.

The book is vividly written and well illustrated. It will undoubtedly find its way to the desks and shelves of geologists, mineralogists, teachers, amateur collectors, and people who "just want to be informed."

GERALD M. FRIEDMAN.

UNIVERSITY OF CINCINNATI,
CINCINNATI 21, OHIO,
Feb. 18, 1952.

Geology and Ore Deposits of the Front Range, Colorado. By T. S. LOVERING AND E. N. GODDARD. Pp. 310; figs. 90; pls. 30. U. S. Geol. Survey Prof. Paper 223, 1950.

"Geology and Ore Deposits of the Front Range, Colorado" contains the sum and substance of many papers written during the period of study of Colorado's mineral deposits since 1926. Included are the works of such men as G. F. Loughlin, C. W. Henderson, W. Lindgren, F. L. Ransome, R. D. George, R. D. Crawford, P. G. Worcester, and others of the United States Geological Survey and the Colorado Geological Survey. Also included are the essentials of the authors' own well known papers on some of the mining districts of the region; for example, Lovering's two professional papers on the Breckenridge and Montezuma districts, Lovering's and Goddard's work in Boulder County, and Goddard's work in the Jamestown district. In addition, much new material resulting from recent work is now made available. One cannot but feel that the background and experience of the authors is invaluable and that the paper represents a summary of almost a lifetime of work.

The authors stress that the present paper is not intended to substitute for the more detailed papers, but is an effort to bring together available information in a more condensed and summarized form. Although the emphasis is on the ore deposits, particularly of the mineral belt, the regional geology is presented in considerable detail. The authors feel that the mining districts can be better understood with reference to the geologic province.

The first 63 pages cover the general geology of the Front Range under the following headings: Precambrian metamorphic and igneous rocks; Paleozoic, Mesozoic, and Cenozoic sedimentary rocks; Laramide igneous rocks; Post-Eocene igneous rocks; and Structure. That portion which deals with structure is divided into Precambrian, Laramide, and Post-Laramide. The relation of movements to pre-existing structures is emphasized. Figure 14 is a paleotectonic map of Colorado that shows the major ancient structural units. The order of structural events during the Laramide Revolution, given in seven steps on page 58, is of interest because of the relation of most of the ore deposits to these events.

The remainder of the paper, approximately 250 pages, deals with the ore deposits of the Front Range concentrated in the Mineral Belt. The material is

divided into three groups: Precambrian deposits, Laramide (late Cretaceous–early Tertiary) deposits, and Post-Laramide deposits. The emphasis is on the Laramide deposits which comprise nearly all of the mineral deposits of the Front Range, with the notable exception of the Cripple Creek district. The Mineral Belt, as illustrated in Plate 2, is considered to extend from Breckenridge across the Front Range to the boundary of the range between Boulder and Lyons. One might note here the variation in usage from that of A. J. Eardley who, in his "Structural Geology of North America," extends the Mineral Belt much farther to the southwest.

An excellent summary of theoretical considerations is presented, in which the discussion of supergene enrichment is especially interesting. It is stated that the zone of residual enrichment in which the relatively insoluble minerals remained coincides with the oxidized zone of sulfide deposition. The relative effects of solubility and acidity of the solutions are considered, and it is further stated that the copper sulfides, soluble in acid sulfate waters, precipitate when the solution becomes neutral or alkaline. "Gold, though noted for its general resistance to solution, is soluble in the upper part of a vein under certain conditions that are not well understood." The authors consider that organic compounds in meteoric waters may be responsible. Neutralization of the acidity or oxidation of the organic compounds then causes precipitation of free gold. This solution and precipitation of free gold occurs chiefly in the oxidized zone. The collection of gold in veins above gouge zones in Farncomb Hill in the Breckenridge district is cited as one example. It would seem, however, that one should consider other possibilities. The implication is made that secondary enrichment is a result of simple precipitation due to change in pH; thus the replacement of sulfides would not always be necessary. More citation of evidence for this theory would help. The burden of proof for the existence of true secondary gold would seem to rest with the authors.

Another point stressed by the authors is the definite relation of the fissure vein deposits to physical characteristics. For example, in the Breckenridge district the pre-mineral faults in one large sheet of monzonite are most productive, while similar faults in other rocks are comparatively poor. Deposits in many places are found to be concentrated in shoots that occupy large openings just above small entrances.

Descriptions of the individual mining districts take up the later part of the paper. For each district the location, history, general geology, discussion of the ore deposits with special reference to the principles of theory, and finally descriptions of separate mines within each district are given. These descriptions are very complete and give a wealth of information in very well condensed and summarized form. The following districts are included: Breckenridge, Montezume, Silver Plume-Georgetown, Empire, Central City-Idaho Springs, Boulder County tungsten, Jamestown, and others. The Guffey and Cripple Creek districts are also described under Post-Laramide deposits. The Cripple Creek treatment is especially good. It should be noted that the authors swing back in the direction of former ideas of volcanism in this district after a period of dominance of Koschmann's theories. The fact that metallization is just one part of a geologic event is well illustrated here.

On the whole the paper is well written and extremely readable, with only an occasional bit of loose terminology; for example, on page 300 one finds "dissolve . . . feldspars." It would have been helpful from a practical point of view if the plates, that are contained in an envelope with the back cover, could have been bound more satisfactorily as the paper cover is not strong enough to hold the rather thick packet. The plates themselves, and the many illustrations, enhance the value of the paper tremendously.

The paper is certainly a definite achievement for the authors. It should serve as a valuable reference in the field, for review by older workers, and especially for the introduction of younger workers and students to the Front Range and its ore deposits.

JOHN R. COASH.

Golden Years, 1851–1951. Edited by E. A. DOYLE. Published by the Victorian Government to celebrate the centenary of Discovery of Gold in Victoria, Australia. Pp. 204. 1951.

This handsome volume is a history of the discovery and mining of gold in the state of Victoria. The "narrative," by Frank Fitzgerald, is entertainingly written. The book is beautifully illustrated, by reproductions of quaint contemporary sketches, by old and modern photographs and, in color, by attractive reproductions of paintings, both contemporary and recent. An appendix gives production data and other statistics.

Anyone interested in gold mining (and who isn't?) will be charmed by this book which recaptures the atmosphere and romance of the days of the "diggers."

H. E. MCKINSTRY.

HARVARD UNIVERSITY,
CAMBRIDGE, MASS.,
Dec. 14, 1951.

Internal Constitution of the Earth, 2nd revised edition of Vol. VII of the Physics of the Earth. Edited by B. GUTENBERG. Pp. 437; figs. 42; tbls. 88. Dover Publications, Inc., 1951. Price, $5.50.

In this edition several of the former chapters have been largely rewritten and others have been brought up to date. The chapter headings are now: 1, Introduction, by B. Gutenberg; 2, Origin of the Solar System, by Harold Jeffreys; 3, Revelant Facts and Inferences from Field Geology, by R. A. Daly; 4, Elastic Properties of Materials of the Earth's Crust, by L. H. Adams; 5, The Chemical and Petrological Nature of the Earth's Crust, by H. S. Washington and L. H. Adams; 6, Observed Temperatures in the Earth's Crust, by C. E. Van Orstrand; 7, The Cooling of the Earth and the Temperature in its Interior, by B. Gutenberg; 8, Forces in the Earth, by B. Gutenberg; 9, Hypotheses on the Development of the Earth, by B. Gutenberg; 10, Evidence on the Interior of the Earth Derived from Seismic Sources, by J. B. Macelwane; 11, Evidence From Deep-Focus Earthquakes, by B. Gutenberg and C. F. Richter; 12, Structure of the Crust. Continents and Oceans by, B. Gutenberg and C. F. Richter; 13, Density, Gravity, Pressure and Ellipticity in the Interior, by W. D. Lambert and F. W. Darling; 14, The Elastic Constants in the Interior of the Earth, by B. Gutenberg; 15, Strain Characteristics of the Earth's Interior, by H. Benioff and B. Gutenberg; 16, Summary, by B. Gutenberg. Two new authors have joined the list.

This book "covers more ground than a dozen standard textbooks and monographs combined. It includes pages of important data available in no other work." It will prove necessary for the specialist in the different fields and will be helpful for geologists, geophysicists, petroleum, mining and metallurgical engineers, and for chemists seismologists. The contributors, of course, are outstanding authorities.

In order to reduce the cost in these days of high cost of printing, the publishers have had it composed by varityper thus cutting the cost almost in half. The appearance of the pages is not so pleasing but it is usable.

Die Lagerstatten nutzbarer Mineralien. By B. GRANIGG, with contributions by J. HORVATH AND V. E. GERZABEK. Pp. 217; figs. 176. Springer-Verlag, Vienna, 1951. Price, bound, $5.00.

This book is divided into 3 parts. The first part (52 pp.) deals very briefly with the origin of mineral deposits under 3 series: A, those associated with eruptive rocks including magmatic (4 pp.), contact metasomatic (3 pp.), pegmatites and pneumatolytic (2 pp.), hydrothermal veins and metasomatic deposits (3½ pp.); B, sedimentary deposits including mechanical, chemical, weathering, supergene enrichment, and organic (15 pp.); and C, metamorphic rocks and deposits (7 pp.). Part II (36 pp.), deals with appraisal of deposits. Part III (128 pp.), treats of prospecting, exploration, and mining, illustrated chiefly with cuts from supply catalogues. This is the main body of the book. It goes into geophysical methods and the details of mining and exploration equipment.

In the absence of footnotes or references it is difficult, without detailed reading, to tell how up-to-date is the content. The geological part is so oversimplified as to be meaningless or erroneous in places.

Dana's System of Mineralogy, 7th Edition, Volume 2. By CHARLES PALACHE, the late HARRY BERMAN, AND CLIFFORD FRONDEL. Pp. 1124. John Wiley and Sons, Inc., New York, 1951. Price, $15.00.

The 1124 pages of the second volume of this monumental work bespeaks the vigor and ability of the three authors to carry on a reputation and tradition of an original work by James Dwight Dana in 1837. Successive editions appeared in 1844, 1850, 1854, 1868, and 1892. A lapse of 52 years appeared between the last edition and the first volume of the 7th edition, and 29 years since the last appendix. Volume 1 of the edition appeared in 1944 and was reviewed in this journal (Vol. 39, p. 513). Volume 3 is in preparation. During that time profound changes have taken place in the study of mineralogy and crystallography and in mineral classification and crystal chemistry. Such advances are incorporated in this edition. The general method of the work and the guiding framework of definitions and conventions as set forth in Volume I have been covered by Dr. Paul F. Kerr in his review of Volume I in this journal. This volume carries the concept of minerals as phases that vary serially in composition within natural limits so that the unit of description is the series. The complexity of some of the polycomponent systems treated in this volume has made it advisable to subdivide them into smaller regions of composition and to describe these separately.

As in the first volume the authors have reduced the mineral names and redefined a number of others. In many cases, inadequacies or errors in existing descriptions have been remedied by first-hand examination of authentic specimens. The classification is essentially chemical in nature, the major classes being based upon the nature of the predominant anion, and the types within classes upon the ratio of cations to anions. The system of numbering species is the same as that used in Volume I.

This volume deals with Halides, Nitrates, Iodates, Borates, Carbonates, Sulfates, Selenium and Tellurium compounds, Chromates, Phosphates, Arsenates and Vanadates, Antimonates Antimonites and Arsenites, Vanadium Oxysalts, Molybdates and Tungstates, and Organic compounds. In the text matter there is the introduction of X-ray data, the optical character of opaque minerals, a new form of presentation of crystallographic data with recalculation of angles and redrawing of all crystal figures, revision of specific gravities based upon new observations on small crystals, and a notable expansion and annotations of the reference sections.

The book is printed in large type with large bold face marginal subheadings, and thus makes easier reading than in the old editions. None of the figures are numbered. The number of pages in the 6th edition, along with appendices, was 1411. The first two volumes of this 7th edition already number 1958 pages. Thus, it is evident, allowing for the fewer words per page, that there has been a great increase in content.

The System of Mineralogy has always been the standard, and the addition of this second volume assures that it will continue to uphold the great tradition of Dana's system and will be the outstanding authority on mineralogy. The author's are to be congratulated for an exceptional work, and the publishers for a courageous venture and a fine example of book making.

Energy Sources—The Wealth of the World. By EUGENE AYRES AND CHARLES A. SCARLOTT. Pp. 344; illust. McGraw-Hill Book Company, Inc., New York, 1952. Price, $5.00.

Petroleum, coal and atomic energy are much in the minds of everyone these days. Consequently, this book on energy sources is timely. It started as a long paper on "Major Sources of Energy" by Mr. Ayres before the American Petroleum Institute in 1948. Demand for copies was greater than could be supplied. It was decided to expand the paper and make it available in book form. This is the result. It is a census of energy sources, past, present and future and covers oil, coal, water power, solar and nuclear energy, wind and tidal power. Here are some of the chapter headings and subjects: How Much Petroleum, Coal, Other Fossil Fuels, How Much All Together; Patterns of Energy Use; From One to Another (change overs); Price of Possession; Waster; Life Expectancy; Nucleus; Patron; Power From the Sun; Windows; Vegetation; Rain; Wind and Tide; Energy Balance Sheet; Appendices. The book is written in a semi-popular manner, is very readable, and intensely interesting.

BOOKS RECEIVED.

CHARLES H. SMITH.

U. S. Geological Survey—Washington, D. C., 1951.

TEI-118. The Quantitative Determination of Calcite Associated with Carbonate-Bearing Apatites. SOL. R. SILVERMAN, RUTH K. FUYAT, AND JEANNE D. WEISER. Pp. 23; tbls. 7. *Results indicate much of carbonate content is not due to calcite.*

TEI-144. Hydrothermal Uranothorite in Fluorite Breccias from the Blue Jay Mine, Jamestown, Boulder County, Colorado. GEORGE PHAIR AND KIYOKA ONODA. Pp. 16; fig. 1; tbls. 2. *Description of uranothorite and its occurrence, and of halos in fluorite.*

TEI-151. Summary of the Research Work of the Trace Elements Section, Geochemistry and Petrology Branch. JOHN C. RABBITT. Pp. 40.

TEM-10B. Lost Creek (Wamsutter) Schroeckingerite Deposit Sweetwater County, Wyoming. D. G. WYANT. Pp. 9; pls. 2. *Exploration and assay results.*

TEM-13A. Vein Deposits of Uranium at the Caribou Mine, Boulder County, Colorado. ROBERT U. KING. Pp. 18; pls. 3.

TEM-24A. Torbernite Occurrence at the Robineau Claims, Clear Creek County, Colorado. ROBERT U. KING AND HARRY C. GRANGER. Pp. 7; fig. 1.

TEM-30A. Reconnaissance Examination for Uranium at Six Mines and Properties in Idaho and Montana. J. S. VHAY. Pp. 21; figs. 2; tbl. 1. *Areas examined returned low uranium assays.*

TEM-145A. The Papsy's Hope Autunite Prospect, Marysvale District, Piute County, Utah. EDWARD P. KAISER. Pp. 10; figs. 3.

TEM-149. Physical and Chemical Comparison of Modern and Fossil Tooth and Bone Material. ELIZABETH B. JAFFE AND A. M. SHERWOOD. Pp. 19; tbls. 6. *Fossil bones have lost free carbonate and combustible organic matter, and have gained in fluorine and ignited insoluble residue. Some have gained in uranium content.*

TEM-167A. A Preliminary Report on Radioactive Fluorite Deposits, Thomas Range, Juab County, Utah. M. H. STAATZ AND H. L. BAUER, JR. Pp. 11; figs. 3.

TEM-251. Red and Gray Clay Underlying Ore-Bearing Sandstone of the Morrison Formation in Western Colorado. ALICE DOWSE WEEKS. Pp. 16; figs. 2; tbls. 3.

CIRC. 176. Preliminary Report on Uranium Deposits in the Pumpkin Buttes Area, Powder River Basin, Wyoming. J. D. LOVE. Pp. 37; figs. 26; tbls. 2; pls. 3. *Radioactive minerals in rolls in Wasatch sandstone. Uranium derived from tuff and carried downward along aquifers into Wasatch formation where it was concentrated.*

U. S. Atomic Energy Commission.

RMO-881. Carnotite Deposits Near Edgemont, South Dakota. K. E. BAKER, L. E. SMITH, AND I. RAPAPORT. Pp. 13; pls. 4. Denver, Colorado, 1952. *Carnotite occurs as interstitial fillings and joint fillings in Lower Cretaceous sandstone.*

RMO-835. Preliminary Bibliography on Uranium and Thorium Radioactive Carbonaceous Deposits. MARGARET COOPER. Pp. 40. Oak Ridge, Tennessee, 1951. Price, 20 cts. *Selected listing of publications dealing with nature of uranium and thorium deposits, problems associated with their exploration and development, manifestations of radioactivity or the presence of uranium in petroleum, petroleum waters, kolm, shales, and related carbonaceous deposits.*

Eleventh Semiannual Rept., Pts. 1, 2, 3. Pp. 211. Washington, D. C., 1952. *Major Activities in Atomic Energy Programs, July–December 1951; Condensed AEC Annual Financial Report, Fiscal Year 1951; Atomic Energy and Its Applications in Plant Science.*

U. S. Bureau of Mines—Washington, D. C., 1951.

1950 Materials Survey—Antimony. Pp. 280; figs. 20; tbls. 36. *The first three chapters of the report cover the properties, products, and uses of antimony; major mining methods and metallurgical processes; and resources, both domestic and foreign. The United States and world supply-distribution positions are analyzed in chapters IV and V. The supply-distribution analysis, with accompanying tables, covers the period 1925–49. Various phases of the structure of the industry are discussed in chapter VI. Annexes include descriptions of individual domestic and foreign industry operations.*

North of the Circle. FRANK TILLINGWORTH. Pp. 254; illust. Philosophical Library, New York, 1952. Price, $4.75. *Some fine pen pictures of the "frozen North," and exciting tales of adventure interwoven with Northern history; of much interest to geographers.*

Essays in Provocation, Letters, Essays and Addresses. GLENN E. HOOVER. Pp. 226. Philosophical Library, New York, 1952. Price, $3.00. *A delightfully written book expressing the views of an able economist of Mills College on political, peace, national economy, labor, and post-war European affairs.*

The Mineral Resources of Arizona. Pp. 15; fig. 1. Arizona Bur. Mines Bull. 159, Tucson, Arizona, 1951. Price, 10 cts. *A brief outline prepared for high school students.*

California Division of Mines—San Francisco, 1951–1952.

Special Rept. 15. Photogeologic Interpretation Using Photogrammetric Dip Calculations. D. H. ELLIOTT. Pp. 21; figs. 9. Price, 50 cts. *Describes method of calculating dip of hill slopes and of strata on vertical aerial photographs with a pocket stereoscope.*

Special Rept. 16. Geology of the Shasta King Mine, Shasta County, California. A. R. KINKEL, JR. AND WAYNE E. HALL. Pp. 11; figs. 4; pls. 3. Price, 50 cts. *Flat-lying massive pyrite lens, containing chalcopyrite and sphalerite, replaces a porphyritic rhyolite.*

California Journal of Mines and Geology, Vol. 48, No. 1, January 1952. Pp. 134; figs. 6; pls. 5. *4 separate articles including: mineral needs and problems of the lead-acid storage battery industry in California; mines and mineral resources of Glenn County, Calif.; and annual reports.*

Sources of Lightweight Aggregates in Colorado. ALFRED L. BUSH. Pp. 65; figs. 6. Colorado Sci. Soc. Proc., Vol. 15, No. 8, Denver, Colorado, 1951. Price, $1.50. *Descriptions of deposits with an extensive bibliography.*

Illinois Geological Survey—Urbana, 1951–1952.

Petroleum 64. Oil and Gas Development in Illinois During 1950. ALFRED H. BELL, VIRGINIA KLINE, AND DAVID H. SWANN. Pp. 46; figs. 3; tbls. 7.

Circ. 176. Summary of Water-Flooding Operations in Illinois Oil Pools to 1951. FREDERICK SQUIRES. Pp. 42; figs. 27. *Data on 63 active controlled floods and detailed description of 3 floods.*

Rept. Inv. 153. Subsurface Geology and Coal Resources of the Pennsylvanian System in White County, Illinois. JOHN A. HARRISON. Pp. 40; figs. 15; tbls. 4; pls. 3. *Key beds, structure, and coal resources described.*

Rept. Inv. 158. Illinois Mineral Industry in 1950. WALTER H. VOSKUIL. Pp. 58; figs. 19; tbls. 46.

Rept. Inv. 160. Waltersburg Sandstone Oil Pools of Lower Wabash Area, Illinois and Indiana. DAVID H. SWANN. Pp. 20; figs. 13. *Reprinted from A.A.P.G. Bull., Vol. 35, No. 12 (Dec., 1951).*

Kansas Volcanic Ash Resources. J. SHELDON CAREY, JOHN C. FRYE, NORMAN PLUMMER, AND ADA SWINEFORD. Pp. 68; figs. 4; tbls. 5; pls. 7. Kansas Geol. Survey Bull. 96, Pt. 1, Lawrence, 1952. *Petrography, uses, and individual deposits described.*

The Geology of the Weaubleau Creek Area, Missouri. THOMAS R. BEVERIDGE. Pp. 111; figs. 5; pls. 12. Missouri Geol. Survey and Water Resources, Vol. 32, 2nd Ser., Rolla, 1951. *Detailed descriptions of stratigraphy and low-angle thrust faulting.*

North Dakota Geological Survey—Grand Forks, 1952.

Stratigraphy of North Dakota with Reference to Oil Possibilities. WILSON M. LAIRD AND DONALD F. TOWSE. Sheets 2; figs. 13; tbls. 2. *Subsurface stratigraphy and structure, illustrated with paleographic maps and sections.*

Rept. Inv. 7. Additional Well Logs for North Dakota. COMPILED BY WILSON M. LAIRD, MARJORIE NESS, AND CLARENCE KLIPFEL. Pp. 137. *Compilation of unpublished well log data.*

Geology of Perry County. NORMAN K. FLINT. Pp. 234; figs. 8; tbls. 14; pls. 15. Ohio Geol. Survey, 4th ser., Bull. 48, Columbus, 1951. *Stratigraphy and economic geology of coal, clay, limestone, and other sedimentary deposits, with descriptions of physiography and structure.*

Pennsylvania Topographic and Geologic Survey—Harrisburg, 1951.

Bull. W-9. Ground-Water Resources of Beaver County, Pennsylvania. D. W. VAN TUYL AND N. H. KLEIN. Pp. 84; figs. 11; tbls. 10; pl. 1.

Special Bull. 5. Oil and Gas Field Atlas of the Bradford Quadrangle, Pennsylvania. COMPILED BY CHAS. R. FETTKE AND VIRGINIA FAIRALL. Pp. 36; tbls. 2; maps 10. *9 maps on scale of 1 inch to 2,000 feet show oil and gas producing areas of quadrangle, and well locations. Structure map and well logs included.*

Special Bull. 6. Oil and Gas Field Atlas of the Smethport Quadrangle, Pennsylvania. COMPILED BY WILBUR H. SEIFERT, CHAS. R. FETTKE, AND VIRGINIA FAIRALL. Pp. 36; tbls. 2; maps 10.

Inf. Circ. 1. Reconnaissance Data on Geologic Structures in Southern Cameron County, Pennsylvania. *Structural map. Scale 1 inch equals 1.2 miles.*

Progress Rept. 135. Oil and Gas Developments in Pennsylvania in 1950. CHAS. R. FETTKE. Pp. 10; tbls. 7; pl. 1.

Progress Rept. 136. Preliminary Report on Certain Limestones and Dolomites of Berks County, Pennsylvania. CARLYLE GRAY. Pp. 85; figs. 7; pl. 1. *Chemical analyses of 366 limestone samples with brief descriptions of localities from which samples were collected.*

Progress Rept. 138. Geologic Structures of the Northern Plateaus Region of Pennsylvania. A. I. INGHAM. *A revised structural map based on recent data. Scale, 1 inch equals 6 miles.*

The Geology of Cacapon State Park, West Virginia. JOHN C. LUDLUM. Pp. 33; figs. 4; pls. 18. West Virginia Geol. Survey State Park Ser. Bull. 2, Morgantown, 1951. *Popular account.*

Geologic Structure and Orogenic History of Venezuela. WALTER H. BUCHER. Pp. 113; figs. 5. Geol. Soc. America Mem. 49, New York, 1952. *Separate chapters describe structural units of Venezuela as outlined on the author's recent "Geologic-tectonic map of Venezuela."*

Technical Publications 1949. Pp. 563. Standard Oil Co., New Jersey, 1951. *24 articles on technical problems in the petroleum industry. Geologic papers include: Upper Cretaceous in Western Peace River Plains, Alberta, by Joseph Gleddie; Leduc Oil Field, Alberta, A Devonian Coral-Reef Discovery, by D. B. Layer and Members of Staff; Derivation of Magnetic and Gravitational Quantities by Surface Integration, by D. C. Skeels and R. J. Watson.*

Programs, Census of Current Projects, and Publications. Pp. 50. Russian Research Center, Harvard University, Cambridge, Massachusetts, 1952.

Bibliography of Seismology, No. 9. W. G. MILNE. Pp. 10. Canadian Dept. Min. Tech. Surveys, Vol. XIV, Ottawa, 1952. *Items 7571–7652, Jan.–June, 1951.*

Ontario Department of Mines—Toronto, 1952.

60th Annual Report, Vol. LX, Pt. IV, 1951. Geology of the Carr Township Area. V. K. PREST. Pp. 24; fig. 1; pls. 3; colored geological map, scale 1 inch to 1,000 feet. *Structural and petrographic description of an area of volcanic and sedimentary rocks in eastern extension of Porcupine gold belt, with results of geophysical exploration and diamond drilling.*

Prel. Rept. 1952–1. Geology of Delhi Township, District of Sudbury. K. D. LAWTON. Pp. 4; pl. 1. *General description of an area in which Pb-Ag-Au mineralization is associated with Nipissing diabase.*

The Australian Mineral Industry, Vol. 4, No. 2. Pp. 32. Australian Bur. Min. Resources, Geol. Geophysics, Victoria, 1951. *Article on "a hundred years of gold in Australia"; mineral statistics.*

Western Australia Geological Survey—Perth, 1948, 1950.

Annual Progress Rept. Pp. 80; figs. 6; pls. 22. *Includes many brief descriptions of mineral deposits.*

Bull. 5. Moulding Sands. K. R. MILES AND H. A. STEPHENS. Pp. 98; figs. 2; tbls. 11; pls. 25. *Physical properties, testing methods, descriptions of deposit.*

Bull. 106. A Geological Reconnaissance Survey of Part of the Area Included Between the Limits Lat. 24° S. and Lat. 29° S. and Between Long. 115° 30′ E. and Long. 118° 30′ E. Including Parts of the Yalgoo, Murchison, Peak Hill and Gascoyne Goldfields. W. JOHNSON. Pp. 103; figs. 14; pls. 6. *General description of a large area of Precambrian rocks with gold, copper, tin, and other mineral deposits.*

Review, Vol. 1, No. 9. Murex Ltd., Rainham, Essex, England, 1951. *2 papers.*

The Concealed Coalfield of Yorkshire and Nottinghamshire. W. EDWARDS. Pp. 285; figs. 39; pls. 5. Great Britain Geol. Survey, London, 1951. Price, £1 2s. 6d. *A revision of earlier memoirs on this area based on recent drilling and mining operations.*

Annales Géologiques de la Péninsule Balkanique, Tome XIX. KOSTA V. PETKOVIĆ. Pp. 289; many figures. Institut Géologique de l'Université de Beograd, Beograd, 1951. *A group of 42 papers on general and applied geology, paleontology, mineralogy, seismology.*

Geologie Von Mitteleuropa. P. DORN. Pp. 474; figs. 91; pls. 36. E. Schweizerbart'sche Verlagsburchhandlung (Erwin Nagele), Stuttgart, 1951. Price, 48.80 DM. *Geology of central Europe.*

The Charnockite series of the Varberg district on the south-western coast of Sweden. PERCY QUENSEL. Pp. 105; figs. 37; tbls. 9; pls. 6. Arkiv For Mineralogi Och Geologi, Band 1, nr 10, Stockholm, 1951. *Description of a new charnockite series, complete with chemical analyses. Added descriptions of ore minerals by P. Ramdohr, and of ferrides by S. Landergren. An extensive review of the literature as well as a detailed bibliography makes this a useful reference on charnokites.*

Société Belge de Géologie—Bruxelles, 1951.

Bull., Tome LX, Fascicule 2. Données nouvelles sur la stratigraphie des terrains anciens du Bas-Congo. J. LEPERSONNE. Pp. 20; figs. 2; tbls. 2. *Revision of stratigraphy of basement rocks of Lower Congo.*

Bull., Tome LX, Fascicule 2. A propos des essais de corrélation entre terrains anciens du Bas-Congo et du Katanga. J. LEPERSONNE. Pp. 10; tbls. 2. *Correlation of basement rocks of Lower Congo and Katanga.*

Carte Géologique du Congo Belge et du Ruanda-Urundi. L. CAHEN AND J. LEPERSONNE. Pp. 40. *Geologic map of Belgian Congo and Ruanda-Urundi, scale 1/2,000,000, with legends and explanations.*

Esquisse géologique de la Guyane méridionale, Etude. E. AUBERT DE LA RUE. Pp. 8; fig. 1. Extrait de la "Chronique des Mines Coloniales, Nos. 181–182 du 15 Juillet–15 Aout, 1951. *Geologic sketch of southern French Guiana.*

Ministerio de Minas e Hidrocarburos—Caracas, Venezuela, 1951–1952.

Bol. 65. Actividades Petroleras. Pp. 25.

Bol. 66, 67. Actividades Petroleras. Pp. 25.

Bol. 68. Actividades Petroleras. Pp. 15.

Sumario. Pp. 90. Boletin de la Escuela Nacional de Ingenieros, Ser. III, Tomo XXIV, Lima, Peru, 1951.

SCIENTIFIC NOTES AND NEWS

S. WARREN HOBBS, Spokane geologist with the U. S. Geological Survey, has been elected Chairman of the Geology-Geography Section of the Northwest Scientific Association to succeed J. HOOVER MACKIN of the University of Washington Geology Department.

JUDD WHITMAN, recently resigned as engineer for the Pend Oreille Mines and Metals Company, has accepted a position as Assistant Geologist under H. F. MILLS, for the American Zinc, Lead, and Smelting Company at their properties near Metaline Falls, Washington.

GEORGE W. RUST, formerly Principal Engineer in charge of the Mining Section of R.F.C. in San Francisco and more recently Consulting Geologist on the West Coast, has joined the staff of Kennecott Copper Corporation as Geologist in the Exploration Department. He may be reached at 37 Rancheria Road, Kentfield, California.

THE FIFTH EMPIRE MINING AND METALLURGICAL CONGRESS will be held in Australia from April 12 to May 23, 1953, and subsequently in New Zealand. The program will consist of, (1) pre-sessional visit in Tasmania, (2) technical sessions in Melbourne, (3) visit to Canberra, (4) technical sessions in Sydney, and (5) post-congress excursions to mining centers. Six volumes will be published on Australian Ore Deposits, Coal, Mining, Milling, Metallurgy, Miscellaneous and General Handbook. The first circular is now available. Communications should be addressed to The Secretary, Fifth Empire Mining and Metallurgical Congress, 399 Little Collins St., Melbourne, Australia.

RAYMOND SIEVER, Associate Geologist in the Coal Division of the Illinois State Geological Survey, Urbana, is the winner of the 1952 President's Award of the American Association of Petroleum Geologists. The award is made annually to the author, under 35 years of age, of the "most significant original contribution to petroleum geology" published in the monthly Bulletin of the Association during the previous year. Selected by a national medal award committee headed by former A.A.P.G. President, CARROLL E. DOBBIN, the winning paper is entitled "The Mississippian-Pennsylvanian Unconformity in Illinois," and appeared in the March, 1951 issue of the A.A.P.G. Bulletin. Presentation of the award, which includes $100 in cash, was made at the Biltmore Hotel, Los Angeles, California, March 25, 1952, at the 37th annual meeting of the AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS, meeting jointly with the two other leading American petroleum exploration societies, the SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS AND THE SOCIETY OF EXPLORATION GEOPHYSICISTS.

RUSSELL S. POOR, Chairman of the University Relations Division of the Oak Ridge Institute of Nuclear Studies, has taken a year's leave of absence to join the National Science Foundation. Dr. Poor will head the Research Education Section of the Division of Scientific Personnel and Education of the NSF. Dr. Poor is a Fellow of the Geological Society of America and the Society of Economic Geologists.